An Inductive Approach to Making Inferences to Underlying Constructs from the Temporal Patterning of the Behaviour of the Rat

by

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ABSTRACT

After a brief discussion of the general approach on which the thesis is based, some properties of time series data are presented. It is argued that these properties, together with certain assumptions, permit inferences from temporal patterning of data to underlying constructs, without the need for specific, a priori hypotheses.

The apparatus used in this study included a large cage designed to record several types of behaviour of a rat, and equipment which permitted automatic recording of which types of behaviour had occurred in ten-second intervals throughout the day for extended periods of time. Each of two rats spent several weeks in the cage. The statistics calculated include: the total number of responses of each animal on each variable; the total number of responses for each day for each variable for each animal; the average across days of the number of responses within successive 15-minute intervals of the day, for each variable for each animal; the lagged correlations for each pair of variables, for lags from zero to eight days; the lagged conditional probability of each variable given each other, and one form of lagged partial correlation. Only selected lagged relations are presented and discussed.

The animals' behaviour exhibited very strong temporal patterning, indicating that their "biological clocks" must be very accurate. The high degree of complexity indicates

that more elaborate analyses are called for and some possibilities are discussed. Certain aspects of the results are compared to some earlier literature, though there is little with which comparisons are appropriate.

The approach taken appears to hold considerable promise in terms of the description of ongoing behaviour of an animal and in terms of the development of an inductive method of identifying underlying constructs which could be considered responsible for behaviour. Considerably more development is needed in this area.

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INTRODUCTION

The general approach on which this thesis is based could be described as "inductive", "multivariate", and "a posteriori" as opposed to the "univariate", "a priori", "hypothetico-deductive" approach more common in Psychology. Perhaps a somewhat simple-minded caricature of the dominant view of how Psychology is done will help clarify the difference:

> Joe Psych is sitting around waiting for something to happen when suddenly, ex nihilo, there appears a hypothesis relating some stimulus-side mediating construct to some response-side construct in some simple monotone way. Joe devises operational definitions relating a particular stimulus variable, S, to a response variable, R, in the same simple monotone way. He designs a simple laboratory situation in which as many as possible of the extraneous influences on his subjects are eliminated and those which cannot be eliminated are held constant at some fixed level. Joe systematically varies levels of S and records levels of R. A quick analysis of variance indicates that the hypothesis was true with probability .95 or that it may be either true or false. The experiment is then either written up and submitted to the appropriate journal or written off and submitted to the circular file.

Is Joe Psych functioning sub-optimally in terms of contributing to science and, if so, how could he improve? Joe's first problem is sitting around waiting for a hypothesis (or better yet a theory from which hypotheses can be formally deduced). This is a rather inefficient way to get ideas. The criticism here is of the hypothetico-deductive model of science, which makes the origin of a new idea seem like a mystical experience or some such thing -

ideas (theories) just come full-blown from the muses or somewhere. Attributing the development of new ideas to reading the literature or talking to colleagues really does not help to explain anything about the origin of ideas, only their dissemination.

Closely allied to the hypothetico-deductive model as a philosophy of science is Joe's reliance on the hypothesis-testing approach to statistical inference. It is at best very inefficient when all knowledge has to be established through a series of true/false questions. This approach has even more serious problems, especially that an effect may be statistically significant though interpretively trivially small, accounting for essentially none of the observed variance, while a very large effect may sit there right in the data without being noticed because the investigator is wearing the blinders of his hypothesis.

Joe's experimental design provides for systematically manipulating one variable (or a few) and measuring only one (or a few). In manipulating a variable, Joe is deciding what the variance will be on that variable rather than letting it take some value typical of the population from which his subjects are drawn. His results may therefore be more typical of his experiment than they are of his subjects. If he uses extreme manipulations (or samples from the extremes of a non-manipulated variable) he may create sufficient variance to make an uninterestingly small

relationship appear quite sizeable. If he uses more than one "independent variable" in a factorial arrangement, Joe will not only have non-representative distributions on each variable individually; he may well have rendered effects orthogonal which are highly correlated in the larger population. If Joe's independent variables are arbitrary manipulations which could be imposed in any combination, this orthogonality is quite appropriate. However, if his independent variables are assumed to have a naturally occurring distribution which is of some interest, Joe will fail to learn a good deal about it. Part of Joe's manipulations consists of attempting to hold constant that which he is not varying systematically. He is assuming, if he intends to make any generalizations, that the relationships among his "independent" and "dependent" variables are the same for all levels of his fixed parameters. Relationships are likely to be much more complicated than this and he might have had completely different results if he had chosen different levels for some of his fixed parameters.

The last paragraph should not be taken to imply that Experimental Design as usually practiced in Psychology is a complete waste of time. There are times when it is entirely appropriate, but all too often it is applied inappropriately to the exclusion of other approaches to the collection and analysis of behavioural data and without due consideration for the statistical properties of the procedures used.

Most laboratory studies conducted in Psychology involve placing subjects briefly in situations which are not typical of their everyday experience and are so structured that choice of alternative behaviours is severely curtailed. The behaviour observed in such situations could hardly be considered typical of even the particular subjects. There are certain situations where this methodology is quite appropriate; however, it would seem a more commendable general strategy to attempt to study subjects in an environment familiar to them, with considerable freedom to engage in a variety of activities. In this way one could argue that any relationships found are in some sense characteristic of the subject rather than imposed on the subject by the circumstances of the experiment.

The idea of operational definitions, like the hypothetico-deductive model and the hypothesis-testing approach to statistics, is a priori: the investigator decides on his interpretation of the experimental variables before he has any data, rather than collecting his data first and then looking at them to decide how to interpret his variables. This happens not only for items on paper-and-pencil tests but also in many complex manipulations in Social Psychology and can even be a problem in a fairly simple rat experiment where, for example, pressing a bar which reduces light intensity might be defined as a measure of preference for lower light intensity. Rats will

apparently learn to press a bar which either lowers or raises light intensity from the same initial level (Barry and Symmes, 1963) and mice will run back and forth many times between two bars, one of which raises light intensity and the other of which lowers it, raising and lowering the light intensity many times in a short period of time (Kavanau, 1967).

The concept of operational definitions leads to further difficulties. Can two operations define the same construct? Presumably this is possible since such fundamental concepts as temperature and mass are measured in more than one way without major arguments among physicists. What happens when such measures are quite imperfectly correlated, as is almost always the case in Psychology? Here we invoke such concepts as unreliability in the measuring instrument, or measurement error, which occurs to some extent even in measuring temperature. The magnitude of the errors in Psychology, however, necessitates separate concepts of "true score" and "test score", with all the discussion surrounding these. When it is found that two separate operational definitions of the same construct not only have a modest correlation with each other, but have quite different correlations with other variables, it is time to scrap the concept entirely and find some other way to make inferences to underlying constructs (traits, states, dispositions and such).

The only reasonable way to retain underlying constructs which has been proposed so far in Psychology would appear to be to "combine" multiple measures in some way. The alternative of finding single "pure" measures may work the odd time, but certainly could not be considered a viable general strategy. Sometimes several relatively pure measures can be summed in order to reduce the relative magnitude of several systematic errors and this could perhaps be described as the traditional strategy of paper-and-pencil tests. An alternative procedure involves analyzing the relations among several measures with the hope of identifying components common to certain subsets of the measures, allowing each measure to include contributions from more than one underlying component. This type of approach involving multiple measures of multiple components is often identified with factor analysis as a means of identifying the underlying components, given the data. There are other methods which use multiple measures in order to identify underlying constructs, including analysis of temporal patterning. This possibility will be discussed more fully later; the point for the moment is that the concept of operational definitions should be replaced by techniques using multiple measures to arrive at underlying constructs. This is not to say that every study must have many measures, but that multiple measures are necessary for many studies which seek to identify underlying components which manifest themselves in a wide variety of situations.

Simultaneous Incompatibility of Behaviours. Most of the literature pertaining to "true scores" vs "test scores" and to multiple measures arises in the context of paper-and-pencil tests and relatively long-lasting attributes of the organism. Using more direct behavioural measures with more transitory attributes leads to more difficulty in relating measures to the organism. There are limits to how much an organism can do at one time and as a result many behaviours interfere with the expression of many others. Insofar as two behaviours arise from a common underlying component, the tendencies to perform these behaviours should be strong simultaneously. However, if the simultaneous expression of the two behaviours is impossible and for some reason the expression of one reduces the tendencies toward both, the two may not appear to be related. Even if the two behaviours do tend to be expressed in close temporal proximity, it may not be clear whether this represents one underlying tendency with two measures or two separate underlying tendencies which happen to be related, each represented by one measure. We may believe that hunger and thirst are separate motivational components, which presumably increase in close temporal proximity. Is there any way to distinguish that two measures in fact represent one measure of hunger and one of thirst rather than two measures of one motivational component? Of course in the case of hunger and thirst there are several ways to do this based on our extensive prior knowledge of these two

phenomena. Most of these methods would not be applicable to exploratory research in a new area. There is at least one method which is applicable under very scant prior knowledge and this will be a topic of further discussion.

The previous paragraph suggests that the impossibility of simultaneous expression of incompatible behaviours can be a hindrance to the discovery that two or more behaviours are instantiations of one underlying component. Of course, this incompatibility will also prevent the simultaneous expression of behaviours representing different underlying components which happen to covary.

Temporal Patterning

Psychologists are wont to talk about the "dynamics" of interpersonal interaction; to express concern for discovering the "causes" of phenomena rather than being content with "mere description"; to emphasize that organisms are complex "systems", the interactions of whose subsystems are characterized by "steady states" rather than states of equilibrium; etc. Many of the concepts which psychologists prefer to use have strong implications of temporal sequences, and often of ongoing reciprocal interaction over extended periods of time. Yet, unlike physicists, psychologists very rarely treat time as a variable of direct interest.

An examination of the temporal patterning of behaviour can provide not only a description of what the animal does when "on the average", valuable as this would be, but also information relevant to what may or may not be important influences on certain behaviours. It will be argued presently that an analysis of temporal patterning allows inferences to the nature of underlying components and their relations both to each other and to the observed behaviours. This is not to say that there is some magical procedure which will yield all the answers, but only that there are methods using time series data which can be very helpful in certain situations.

The Lagged Correlation Function and its Properties. There is a certain amount that can be done statistically with an undifferentiated set of numbers; one can examine attributes such as the mean, median, variance, skewness and kurtosis. If the set of numbers can be partitioned in some reasonable way into two sets, these same attributes can be compared for the two sets, with some statistical derivatives such as the ratio of the variances or the t-test. If two sets of equal size can be put meaningfully into one-to-one correspondence with each other, there are a number of additional statistics which are applicable, that of greatest interest here being the Pearson product-moment correlation coefficient. If the pairs of numbers in the two sets can be put into a common order, preferably an ordering with the properties of an

interval scale, then additional calculations become meaningful. In particular, it is possible to express the correlation between the two sets not only in terms of the original pairs but also as a function of pairings derived from "shifting" the two orderings with respect to each other. In the most common application the ordering is on the basis of time and new pairs are defined in terms of events being separated by certain intervals of time. Repeated applications of the operation of shifting one series by one position with respect to the other and calculating the correlation of the resulting pair yields a function of three arguments, the original variables and the lag (number of shifts) between them. The value of this function for arguments x, y and l will be the Pearson correlation coefficient of x and y with y shifted l time units later than x.

It will be important in the discussion which follows to distinguish between the case where a lagged correlation function is periodic and where it is not. Stricktly speaking a function is periodic only if it starts to repeat exactly after some period:

$f(x)=f(x+kp)$ for some $p>0$ and all $k=\ldots,-2,-1,0,1,2,\ldots$. However, with real data, it is unlikely that a lagged correlation function would ever repeat exactly and so we will weaken the equality above to approximate equality. It is often convenient in discussing continuous functions, especially probability functions and other functions based

on random variables, to allow for exceptions at finitely many points. In the discussion which follows it will be convenient at times to allow the approximate equality to fail to hold at a "few" lags, in particular lags near zero. The reason for this strategy will become obvious in the appropriate context. Despite some ambiguity in the criteria for labelling a particular lagged correlation as periodic, it will seldom be difficult in practice, provided there is a substantial quantity of data.

A function which is not periodic according to the above criteria may still be characterized by a certain period. A damped harmonic function is characterized by a particular period, but the amplitude becomes smaller with each cycle. For other functions the period itself may be only approximate, whatever the amplitude of successive cycles. These functions which are similar to periodic functions will be termed "cyclic". Periodic functions can be considered a subset of the cyclic functions. There is considerable variation within this class of functions and it is difficult to discuss their properties. A cyclic function which is not periodic will have the property that its autocorrelation will have a peak at some non-zero lag, with smaller peaks at multiples of this lag. If the period itself is not exact, peaks of the autocorrelation will become successively broader as well as lower.

A function which is not cyclic will be termed "aperiodic". The autocorrelation of an aperiodic function will generally approach zero fairly quickly as the lag departs from zero and stay near zero for all long lags. Although an aperiodic function may in general fluctuate quite wildly, there are other attributes which an aperiodic lagged correlation will generally have. If the variables are related at all, we expect the most extreme values of the function to occur at relatively short lags; at relatively long lags the function will remain near zero. It is difficult to conceive of behaviours which appear unrelated in the short run but show a relationship in the long run. What constitutes short lags vs long lags will depend on the rate of change of the values of the individual variables being correlated; when recording from a single-cell electrode, one minute might be considered a long lag: when re-administering an intelligence test, one month might be considered a short lag.

The lagged correlations (both auto- and cross-, collectively) generated by a pair of variables will have the following properties, among others:

1) If neither autocorrelation is periodic, the crosscorrelation will not be periodic.

2) If both autocorrelations are periodic and the crosscorrelation is high for some lag, then the crosscorrelation is periodic.

3) If one autocorrelation is periodic and the

other is monotone decreasing, the crosscorrelation will be cyclic with decreasing amplitude.

4) If one autocorrelation is periodic and the crosscorrelation is high at any lag, then the other autocorrelation must be cyclic.

Inference from Temporal Patterning to Underlying Constructs. From properties such as those above it is possible to establish criteria for making inferences to underlying constructs and the relationships between such constructs and observable behaviours. For the present discussion the term "construct" will be used to refer to general underlying tendencies toward the expression of certain classes of behaviours. The term "component" will be used to refer to attributes of the lagged correlations. Thus "construct" will be applied to the organism while "component" refers to statistical properties of the data. Any number of relatively simple functions having the properties described so far could be combined as components of a more complex function. The problem of how to make inferences from data to organisms can be recast as how to find a statistical decomposition of a complex function into components which make sense when put into one-to-one correspondence with underlying constructs. This problem is simply ignored by the hypothetico-deductive model of science, but hopefully will become part of an inductive method. In the case of a

purely periodic function, it is possible to decompose the total function into components, each having a single period and "location" defined by the point within the cycle where the ordinate (lag of zero) cuts the waveform. This decomposition has the advantages that the separate frequency components are orthogonal and that a single frequency is readily interpretable. This decomposition corresponds closely to the ear's decomposition of a complex musical note into several distinct pitches. For any autocorrelation all periodic components peak at lag zero.

In the case of a purely aperiodic function each peak could be considered a separate component since the peaks are generally not predictable from each other. The cyclic case is more difficult to deal with. In the case where the amplitude of successive cycles decreases, each frequency which is present could be considered as a component with the rate of decrease in amplitude taken to be an attribute of the component which may be different for different components of the same function.

There is no reason why any particular lagged correlation must be composed entirely of any one type of component; it could include periodic, aperiodic and cyclic components. It would not be at all surprising to find a certain behaviour having periodic components (perhaps regulated by such factors as photoperiodicity) and also

aperiodic components (for example, that necessitated by the simultaneous incompatibility of many behaviours).

Given the above discussion of how complex lagged correlation functions may be considered to consist of a number of simpler components, we further assume that every component in a lagged correlation function corresponds to one and only one underlying construct and that each construct is represented by at most one component in each lagged correlation function. Once a particular form of statistical decomposition has been chosen, this assumption allows specification of a model of the behaviour of the organism with respect to the behaviours measured. With these assumptions, there are a number of inferences which can be made from lagged correlations to underlying constructs.

To the extent that a behaviour is a manifestation of a construct, the probability of that behaviour should be high when that construct is at a maximum. If the behaviour is being recorded, we say that the resulting variable is a measure of the construct. This implies that the lag from the time when a construct reaches a maximum level to the peak in a measure of it will be very small. This is equivalent to saying that the peak of an autocorrelation function at lag zero corresponds to the maximum of whatever "causes" the behaviour.

If two variables, A and B, happen to be "pure" measures of the same construct (i.e. the only component not induced by the construct is a random error), one would expect their autocorrelations to be identical. Further, the probability of A occurring after B had occurred would be the same as the probability of B following A, and this implies that the lagged crosscorrelation should be symmetric about lag zero. Further, since the two variables are interchangeable as measures of the construct, the correlation of A with any other variable should be identical to the correlation of B with the same variable. In practice "pure" measures are very rare, but these properties generalize to common components of two or more variables.

If two variables include some common component which corresponds to a single underlying construct and if that component is periodic, we expect it to appear in the lagged crosscorrelation of these two variables. It will appear as a component which is symmetric about lag zero and which "should", though may not, peak at lag zero. The reason the component "should" peak at lag zero is that the tendencies to the two behaviours, being manifestations of the same construct, will increase and decrease together. The reason the correlation may not peak is that the two behaviours may tend to suppress each other. The width of the region of suppression will increase with the tendency of each behaviour to persevere. This tendency will also be manifested in the width of the peak near lag zero of the

respective autocorrelations. The fact that the crosscorrelation "should" peak at lag zero may be ascertained by examining the periods which do not include lag zero and interpolating from these to the region of lag zero. The difference between the interpolated values and the actual values is an indication of the nature of an aperiodic suppression effect. This difference should increase to the extent that the individual variables are highly autocorrelated in the region of lag zero.

It follows from the fact that a function is periodic that all (or "almost" all) of its cycles are identical, within sampling error. As discussed above, if a component of a crosscorrelation represents a single underlying construct, it will be symmetric about lag zero and should peak at lag zero. It follows that if such a component is periodic, each cycle centred a whole number multiple of the period from the origin will be symmetric about its centre.

If a periodic component of a crosscorrelation does not and "would not" (corresponding to the "should" above - i.e. with interpolation) peak at lag zero, it must correspond to a relationship between two underlying constructs, each measured by one of the two variables, rather than to a single construct common to both variables. It does not follow that a periodic component of a crosscorrelation which is symmetric about zero and "should" peak at lag zero must represent a single underlying construct, measured to some

extent by each of two variables. It is possible that there are two constructs with the lag between them equal to the period. However, until there is some evidence that this is the case, it seems reasonable to assume a single underlying construct.

If a component of a crosscorrelation is periodic except in the region of lag zero, it seems reasonable to interpolate the periodicity in this region, even if there will be no peak at lag zero. The difference between the interpolated values and the actual values may be attributed to the simultaneous incompatibility of the two behaviours.

This discussion of making inferences from lagged correlations has focused primarily on the case of periodic correlation functions, for reasons that will become evident when the results of the current study are presented. For the aperiodic case it should be noted that, to the extent that a variable, A, influences another variable, B, with some lag, l, required before the influence is manifest, we expect that the absolute value of the correlation of A followed by B, l units later, will be greater than the absolute value of the correlation of A preceded by B, l units earlier. Once the aperiodic component of a complex crosscorrelation has been estimated by interpolation and subtraction as suggested above, it may be possible to establish an asymmetric influence of one variable on the other at some particular lag.

The discussion so far does not indicate how, if at all, it is possible to identify uniquely components of a complex function. Unfortunately, in the degree of generality of this discussion, there is no way to guarantee that a particularly complex function can be decomposed "the right way". The approach adopted in the present study is to attempt to maximize the probability of finding relatively "clean" lagged correlations which will yield a good deal of information from visual inspection. More rigourous methods can then be applied to the same data in the hopes of verifying the initial observations, evaluating alternative methods, and extending the conclusions in a sort of recursive "boot straps" fashion.

Subjects and Situation

Because this study attempts to explore methods quite atypical of the behavioural sciences, it was considered important to obtain a substantial amount of complete data. Problems with missing data are likely to be especially serious in time series analyses. It was anticipated that correlations would decrease with long lags, but this possibility could only be examined if the series were sufficiently long to estimate fairly long lags without bias attributable to the decreasing effective sample size at long lags. Having obtained relatively long series of complete data, it would then be possible to restrict the length of

the series or introduce gaps in the data in order to examine their effects on the results.

It also seemed important, for a first effort, to examine relatively simple behaviours rather than more complex ones such as social phenomena. It was also felt that behaviours which are a significant part of the life of the subject should be studied in a familiar environment.

The rat is an easy animal to work with and adapts readily to a wide variety of environments. It is not difficult to keep a rat in a laboratory environment which is sufficiently simple to allow careful study but sufficiently complex to afford the animal a reasonable variety of activities. Since the rat is so widely used for research in the behavioural sciences, it was expected that there would be ample literature concerning its habits. As it turns out the rat is rather less studied than many other animals, including its close relatives, the ground squirrels. It has been suggested that the rat is not a very glamourous subject, nor is its natural habitat the kind of place to which many researchers would like to retreat for extended periods of time. Studying the rat in the wild has the additional disadvantages that human beings tend to damage or steal field equipment and kill the subjects of study.

In line with these considerations, a cage was designed and built which afforded ample opportunity for variety in the activities of a rat. This cage permitted recording of a

number of basic activities of the animal. A system of recording was designed and assembled which permitted continuous, automatic monitoring of the activities of the animal for long periods of time, potentially several months.

ENVIRONMENT

The main piece of apparatus was a cage about 36" X 24" X 21"(high), and its contents. The walls of the cage were relatively opaque except for a window in one wall. The floor and ceiling of the cage were made of wire mesh. In one corner of the cage there was a wooden "nest" box about 8" X 8" X 4"(high) with a short "tunnel" entrance to prevent light from entering directly through the doorway. The floor of the nest box was hinged with a switch mounted opposite the hinge such that the weight of a rat closed the switch. Strips of cloth were provided as nesting material for the first animal. The cloth proved a nuisance and was therefore not provided for the second animal.

Near one end of the cage there was a standard Lafayette activity wheel about 14" in diameter mounted on a non-standard base. Each revolution of the wheel caused a cam on the shaft to close a switch. The switch was connected to a timer which opened the circuit to the recording device if the switch remained closed for over 10 seconds. This procedure prevented stoppage of the wheel with the switch closed from being recorded as turning of the wheel. Near the other end of the cage there was a wire mesh configuration suitable for a rat to climb on. This configuration was mounted such that the weight of a rat closed a switch. This switch was connected to a timer such that switch closures of less than 0.5 seconds were not

recorded. This procedure prevented recording of accidental jarring of the apparatus when there was no actual climbing.

There were two food dispensers. One was a standard operant bar and food dispenser operating on a fixed interval 20 second schedule. The other consisted of a piece of brass tubing extending vertically from the top of the cage to about three inches above the floor. The bottom of this tubing was cut and bent such that, when the dispenser was filled with standard laboratory food chunks, the bottom chunk could be bitten readily but could not be removed until its size had been substantially reduced. This dispenser was mounted in a gimbal suspension such that light pressure moved it slightly sideways to touch a metal ring which surrounded it, thereby completing an electric circuit. The ring was the "hot" side of the circuit and was sufficiently above the floor of the cage to make it awkward to reach; in addition the voltage was sufficiently low that it is unlikely the animals could feel it. The output of this "switch" went to a timer which prevented contacts lasting less than 0.2 seconds from being recorded; thus accidental jarring of the apparatus was not recorded.

The cage was equipped with two standard laboratory water dispensers. The spout of one of these was available without effort. A capacitance-sensitive relay was attached to the spout to record any contact of the animal with the spout. The spout of the other dispenser was covered by a

pendulum which the animal had to hold aside in order to drink from the spout. The shaft of the pendulum was connected to a switch which remained closed as long as the pendulum was held aside.

The cage was also equipped with an operant bar connected, through a timer, to a radio such that when the bar was pressed the radio was turned on for about 2 minutes. The radio was a tube-type which required about 30 seconds to warm up. It was tuned to a "pop" music station which broadcast 24 hours per day. The volume was adjusted such that the announcer's words were barely discernible from near the cage. A similar bar and timer were attached to a string of Christmas tree lights strung about the room outside the window in the cage wall. There was also an "empty" bar which had no effect on the environment in the experimental room, but the pressing of which could be recorded.

Between the floor of the cage and the dropping pans below there was an "elimination grid" (adapted from Kavanau, 1963). This grid consisted of three sets of wires strung across the width of the cage, the wires in each set placed half an inch apart along the length of the cage. The middle course of wires was located a quarter of an inch below the top course and displaced a quarter of an inch laterally from being directly below the top course. The bottom course was strung a sixteenth of an inch directly below the middle course. The top and bottom courses of wire were each

connected to the "hot" side of the sense head of one of two Grason-Stadler drinkometers, while the ground wires of both drinkometers were connected to the middle course. The intention of the "elimination grid" was that feces falling from the cage to the dropping pans would temporarily contact one of the wires of each of the top and middle courses of wire but not be able to contact the bottom course, while urine would contact a pair of wires from the middle and bottom courses but not bridge the larger gap between the top and middle courses.

Other than the string of Christmas tree lights mentioned above, the only light in the room came in through a south-facing window approximately 14 square feet in area. The cage was about 30 inches in front of this window. The temperature and humidity in the room were relatively constant. Except for keeping the door closed, no particular effort was made to shield the room from noise in the hall.

Throughout the remainder of this thesis the following labels, with capitalization, will be used in referring to the apparatus and resulting data variables: Food Bar, Direct Food, Capacitance Water, Water Pendulum, Wheel, Climber, Lights, Radio, Nest Box, Empty Bar, Urination and Defecation. These labels will be used for the sake of consistency and also as a reminder that these are labels and do not represent a priori interpretations of every recorded response as representing a particular type of behaviour on

the part of the animals. It is quite possible, for example, that the animals may enter the Nest Box as part of their exploratory activities or food hoarding and may sleep outside the Nest Box, making Nest Box occupancy not always an indication of resting.

PROCEDURE

An 80-day-old female Sprague-Dawley (albino) rat was placed in the apparatus. Both food and both water dispensers contained food/water at all times. Modifications were made to the apparatus over a period of several months to obtain more reliable measures and to make the apparatus virtually indestructible to a rat. After all modifications were made, the animal remained in the cage relatively undisturbed for several weeks before the experiment proper began. Thus it is clear that this animal was very thoroughly habituated to the environment and the presence of the experimenter in the room. This animal was about 200 days old at the beginning of actual data collection. Twenty-four days of data were collected. As the commencement of data collection meant only connecting a tape drive to the interfacing in the adjacent room, nothing changed from the animal's point of view with the commencement of data collection.

After the data had been collected from the first animal, the animal was removed from the cage and the cage was dissassembled and scrubbed to reduce this animal's odour. It is quite possible that this procedure left odour detectable to another rat but presumably only faintly.

The second animal was a male Long-Evans hooded rat. This animal was moved to the experimental room about the same time the first animal was removed from the cage. He

was about 100 days old at this time. He remained there in his small cage for two days while the experimental cage was dissassembled, removed from the room, cleaned, returned and reassembled. The small cage was then placed inside the experimental cage and the top removed. Within five minutes the animal had left the small cage and had explored that end of the larger cage, including entering the Nest Box and Wheel. The small cage was removed after 15-20 minutes and data recording began. Data were recorded for 32 days.

A word should perhaps be said about the rationale for using only two animals and for using these two in particular - one male, one female and one albino, one hooded. The intention of this experiment was to try a method and not to demonstrate conclusively any universal truths about ratkind. Two animals seemed quite sufficient for such exploratory research. Other research (Wang, 1923) has found that female rats show very pronounced four-day cycles in running activity wheels, corresponding to their oestrous cycle. It was hoped that this female would yield interesting four-day periodicities in several variables and that these might include changes in short-lag covariance patterns coincident with changes in overall activity levels. A hooded rat was used because hooded rats are genetically closer to wild rats and particularly because they have pigmented eyes, a fact which could easily reduce the effects of photoperiodicity. Lockard (1968) discusses some differences between albino rats and the rest of Rattus Norvegicus.

DATA COLLECTION AND ANALYSIS

The twelve measures mentioned previously were recorded on equipment located in the room adjacent to the experimental room. Each measure was connected to a "latch" which had two electrical states. The first time a given type of event occurred the latch changed states. It then remained in the second state, whether or not further events occurred, until it was reset. These latches were part of a piece of interfacing which connected the experimental cage to a 7-track digital tape drive. Every ten seconds the interfacing wrote the condition of all twelve latches onto a magnetic tape and then reset the latches. Thus the recorded data consisted of 12 binary variables, with a 1 corresponding to the event having occurred at least once in the ten-second interval and a 0 corresponding to the event not occurring at any time during the interval. The interfacing and tape drive could be left running for periods of weeks or even months - until the tape ran out. The tape format written by this tape drive was a standard 7-track, 200 BPI, odd parity format readable at most major computer centres. The data from this experiment could thus be read directly into the main computer at this university.

The total amount of data collected in this experiment is quite substantial. It consists of 12 variables X (24+32) days X 24 hours/day X 60 minutes/hour X 6 samples/minute = 5,806,080 pieces of information. If each of these were

allowed to occupy a full word of core memory in the computer (the smallest amount readily manipulated in high level languages such as Fortran), the capacity of the Amdahl 470/V6 would have been exceeded several times over. In order to overcome limitations in computer space and computer time usage, programs were written in Assembler Language to do the initial data analysis.

All twenty-four days' data from the first animal were analyzed. The first fourteen days for the second animal were omitted from the initial analysis. These first fourteen days were considered developmental data while the animal became familiar with the environment and established relatively stable patterns of behaviour. It was intended subsequently to develop programs to analyze this developmental phase and also to follow the development through all 32 days. The analyses completed so far yield the following information for each animal:

1.) the total number of times each of the twelve events occurred

2.) the number of times each event occurred in each day of data collection (plotted on the Calcomp plotter)

3.) the average number of times each event occurred in each 15-minute interval of the "average" day - i.e. 96 numbers (24 hours X 4 quarters/hour) for each variable, each number being the sum across all days of the sum for that particular

part of the day divided by the number of days (plotted on the Calcomp plotter)

4.) the standard deviation of each of the data variables

5.) the sum of lagged crossproducts for each pair of variables for lags from: 0-30 minutes at 10-second increments (181 lags); 30 minutes - 4 hours at increments of one minute (210 lags); 4-48 hours at intervals of 10 minutes (264 lags), and 2-8 days at intervals of 30 minutes (288 lags). It should be noted that raw data were not summed when the lag increment was longer than 10 seconds; all data were used for each lag calculated but intermediate lags were omitted. The reason for omitting some lags was to economize on computer time. The analyses as performed required about an hour of CPU time on the Amdahl; this was for 943 lags. The total number of lags from 0 to 8 days using a ten-second increment throughout would have been 69,121 - requiring almost 3 days of CPU time!

6.) the conditional probability of each type of event following each type of event at each of the above lags. These were plotted as probability versus lag for each pair of variables.

7.) the lagged correlation of each type of event

with each type at the above lags. These were similarly plotted as correlation versus lag for each pair of variables.

8.) the lagged partial correlation of each pair of variables, consisting of the simple correlation minus the product of the lag-zero crosscorrelation of the pair and the same-lag autocorrelation of the "leading" variable, standardized to lie in the interval (-1, 1).

RESULTS AND INTERPRETATION

This section will not attempt to present all the results, but rather will restrict itself to the "simpler" results and certain aspects of the correlations and conditional probabilities which are particularly interesting and which warrant further consideration. There are a number of observations which will be mentioned before proceeding to the presentation of the statistical analyses.

As already mentioned, the first animal had been in the cage for several months by the beginning of the data collection, during which time a number of modifications were made to the apparatus. This animal was seldom handled during this time and became somewhat wild. She squirmed, squealed and tried to bite if picked up. No attempt was made to handle this animal for several days prior to the beginning of data collection or during the data collection phase. For the first several days she was in the cage this animal ate only from the Direct Food dispenser without ever pressing the Food Bar. Eventually the experimenter shaped the animal to the Food Bar and for several days the animal obtained virtually all its food from the Food Bar. After a few days she began to eat from the Direct Food dispenser as well and maintained an equilibrium for some weeks prior to the beginning of data collection. Upon learning to press an operant bar, this animal began pressing the Empty Bar, the Lights bar and the Radio bar as well as the Food Bar. The

response rate for the Radio decreased to zero over a period of about two weeks and remained there. The response rate for the Lights fell more slowly and reached a non-zero asymptote some weeks before the beginning of data collection. The response rate on the Empty Bar remained quite high.

This animal spent a good deal of time in the Wheel, often without turning it (and therefore not recording her presence on the tape). When upset she was as likely to enter the Wheel as the Nest Box. She often slept in the Wheel even with the mid-day sun shining directly into the cage. At times the majority of the nesting material was in the Wheel rather than the Nest Box. Preference for sleeping one place or the other generally seemed to last for several days. On occasion this animal used the nesting material to block the entrance to the Nest Box.

The second animal had had a somewhat non-standard rearing. It had been one of a number of such animals placed in separate cages at a somewhat earlier age than is typical. This procedure was intended to make these animals more suitable for experiments in aggression. This particular animal was considered by those caring for these animals to be more alert, active, fearless and vicious than most. He was given to the present experimenter partly because he was very difficult to handle.

This animal spent his first few days in the cage without eating from either food dispenser. After the first 24 hours the experimenter periodically placed food on the floor of the cage near the Direct Food dispenser, but not nearly enough to satiate the animal. Small chunks of food were also placed in the bottom of the Direct Food dispenser such that they needed only a light pull to come out. The animal promptly ate the food placed in the cage but failed to take any from the larger chunks in the Direct Food dispenser. This animal never did bite a piece from a chunk of food in this dispenser. After a few days this animal learned to use the Food Bar to obtain food without being shaped to it.

Reliability

This study grew from concern with the difficulty of making inferences from observed variables to underlying psychological processes and the necessity of giving the data precedence to determine what a measure is a measure of. Before attempting to make inferences to unobservables, it is necessary to have a good idea of what observable events lead to what data values. One of the easiest questions to ask in this realm is whether the same type of event always resulted in the same data value. This is a question of the reliability of the recording device. The question of reliability and measurement error is more complicated in the analysis of temporal patterning than it is in more

traditional forms of data analysis because of the possibility of sequential dependencies in the errors. There are a number of clear instances of various types of unreliability in the data to be presented and these should be noted as presented.

The timers used in this study proved to be quite unreliable. On several occasions it was found that a timer had ceased to function at all or that a particular relay was burnt out. These failures resulted in "holes" of various sizes in the first animal's results for the Wheel, Direct Food and Urination. These holes will be quite apparent from the graphs of the daily totals for each variable (see Figure 1).

On several occasions the experimenter found feces stuck shorting the wires of the elimination grid, resulting in Defecation being recorded repeatedly. This happened especially for the second animal. The first animal sometimes dropped bits of shredded nesting material which could become caught on the elimination grid causing Urination or Defecation to be recorded repeatedly if the animal happened to urinate on the cloth. Both of the drinkometers had a tendency to "drift" in their sensitivity and both had a tendency to perseverate: once they had been triggered their sensitivity increased and then gradually returned to normal if they were not triggered again. When the sensitivity had drifted high, a response triggered by

elimination was often followed by perseverative responding of from one response to several minutes of responses. The sensitivity was adjusted several times during the course of the experiment. Nine days before the end of the experiment one of the wires on the elimination grid broke and shorted both elimination measures. The Defecation side of the grid was restored but the wires in the same course as the broken wire sagged with the loss of tension to the point where the resistance was so low, even though there was no short circuit, that Urination was being recorded repeatedly. The Urination measure was therefore disconnected for the last nine days of the experiment. Because of the unreliability of these measures, very little further attention will be devoted to them.

Overall Levels of Various Measures

The simplest, most condensed, useful measure of the animals' use of their environment is the total number of ten-second intervals during which each of the twelve types of event occurred. These are presented in Table 1. These results give a general impression of how much the animal did what. It should be remembered, however, that the totals for the different variables are not directly comparable - pressing the Food Bar for a small food pellet, for example, is not equivalent to biting a (probably much larger) piece from a chunk of food in the Direct Food dispenser. It should also be remembered that the numbers for the first

animal are totals for 24 days, while those for the second animal represent totals for 18 days so that, for example, the second animal spent somewhat more time per day in the Nest Box on the average despite his smaller total. In order to make comparisons between animals easier, the table also presents the average number of responses per day for each variable for each animal.

One of the most obvious aspects of these totals is that there are two zeros and several very small numbers. Could these represent the animals' failure to learn to operate some of the manipulanda, with small numbers representing random behaviour or unreliability (such as several of the second animal's 12 revolutions of the Wheel representing turning resulting from the animal's attempt to climb up the outside of the Wheel)? This is definitely not the case with the Lights and Radio for the first animal. After this animal was taught to use the operant bar to obtain food, she started pressing the other three bars fairly frequently. The frequency of turning on the Radio decreased to near zero over the next few days. The frequency of turning on the Lights decreased much more slowly and had reached a non-zero asymptote by the beginning of data collection. There was, in fact, an increase in the frequency of turning on the Lights during the data collection (see Figure 1), though this increase was well within the bounds of random variability. On the other hand, the frequency of pressing the Empty Bar was still fairly high (about 30 times in the

"average" day) during the data collection phase of the experiment. Thus the decrease in frequency for the other two measures should not be attributed entirely to improved discrimination and lack of reinforcement; the Empty Bar should have been no more difficult to discriminate from the Food Bar than either of the other two.

The results with respect to the four operant bars could be considered somewhat embarrassing to a reinforcement theory of behaviour. The animal was initially shaped to the Food Bar and the reinforcement of the food certainly could account for the high level of responding maintained throughout the experiment. This bar-pressing tendency could easily generalize to the other three bars and account for the initial response to these bars. It could easily be argued that the sound of the Radio was punishing and so led to a zero response rate as its contingency was learned. The relative response rates on the Lights and Empty Bar would seem to pose problems, however. The sustained high response rate on the Empty Bar implies that bar-pressing as such must have been a secondary reinforcer which could not be eliminated by improved discrimination - discrimination was presumably perfect judging by the absolute zero response rate on the Radio for over three months. The difference between the response rates for the Empty Bar and the Lights must then be attributable to one of: greater similarity of the Empty Bar to the Food Bar, the ease of responses on the Empty Bar, or a punishing effect of the Lights. In overt

appearance - shape, size, texture, etc. - the Empty Bar was less similar to the Food Bar than was the Lights bar. The Empty Bar was out of the way in a corner where the animal spent less time than it did in the vicinity of the Lights bar, and the pressure required to operate either of these bars was comparable and substantially less than that required to operate the Food Bar. This leaves the possibility that the Lights may have been punishing. If this were the case, why did the response rate not fall to zero as discrimination became perfect?

It should also be noted that the frequency of the Empty Bar peaked at a quite different time of day than did that of the Food Bar (see Figure 3), a result which seems strange if it were the same motivational component underlying both. These results are by no means irreconcilable with a general reinforcement viewpoint: they are just quite awkward.

The second animal had been in the cage for two weeks prior to the collection of the data reported herein, not several months as the first animal had, and it is not as easy to interpret near-zero response rates. The two weeks of as yet unanalyzed data should aid in this respect. The Empty Bar, the only variable with an absolute zero response rate, was in an obscure location in the cage thanks to modifications made to the Nest Box prior to collecting the

first animal's data. It is quite possible that the second animal just failed to find this bar and recognize it as similar to the Food Bar.

The Direct Food measure shows only four responses and it is quite possible that these could represent non-feeding behaviour. It could not reasonably be said, however, that this animal could have failed to learn the contingency associated with this measure: the same kind of food the animal had been accustomed to was there, exposed, and all the animal had to do was bite it. The food was quite prominently displayed. This animal did, in fact, nibble at the food; but the only pieces he ever ate were small ones the experimenter placed at the bottom of the dispenser such that they would come loose very easily. This animal went hungry for several days before he learned to obtain food from the Food Bar. During this time the experimenter placed food similar to that in the Direct Food dispenser on the floor of the cage in sufficient quantity to keep the animal healthy but not to satiate it. This food was always eaten immediately, even though the animal would not eat from the Direct Food dispenser. This animal's failure to eat from this dispenser thus cannot be attributed merely to a preference for the Food Bar pellets.

The Water Pendulum shows only seven responses for the second animal and it is quite possible that the animal could have accidentally pushed the pendulum aside with no

intention to drink. However, the water level in this dispenser did fall fairly abruptly at one point during the experiment, so it is quite likely that the animal did in fact drink from this dispenser. There were more responses on the Water Pendulum in the two weeks' unanalyzed data than during the period reported here.

The Wheel shows only twelve "revolutions" for this animal. There was very little learning to do with respect to the Wheel and the animal was seen to enter the Wheel and rotate it within fifteen minutes of first being placed in the cage. Thus it could hardly be maintained that the animal had failed to "learn" the Wheel.

The Radio bar was pressed fifty times and this number seems sufficient to suggest that the animal had learned its contingency. The Lights, with 23 responses, are more difficult to interpret. There is some reason to believe that there may have been a malfunction in the apparatus since all 23 responses occurred during the first three days of the data reported here and the number of responses per day increased for these three days (see Figure 2). It is not clear whether the 20 days of zero response rate on the tape represents the failure of the animal to press the Lights bar, or some malfunction of the apparatus which went unnoticed. As of the time that the experiment was terminated, the signal from the Lights switch was getting at least most of the way through the interfacing. It is

possible that further electrical examination of the interfacing would reveal an unreliable component. Examination of the as yet unanalyzed data (recorded prior to that reported here) might indicate whether the increasing response rate was part of a longer trend.

A comparison of the total responses for the two animals on each measure should give some general idea of their similarities and differences with respect to their use of the experimental environment. It will be noted that the second animal made considerably more use of the Food Bar, which is hardly surprising since he did not eat from the Direct Food dispenser whereas the first animal ate from both. It is not at all certain that the difference is entirely attributable to the second animal's need to compensate for not eating from the Direct Food dispenser: it could also be that the second animal made more unreinforced responses on the Food Bar, having had less time in the cage to learn to estimate the length of the period when food was unavailable following a reinforcement.

The pattern for the two water measures is somewhat similar to that for the two food measures: the first animal used both approximately equally while the second used the Capacitance Water to the relative exclusion of the Water Pendulum. Unlike the two food measures, the two water measures may be considered more or less equivalent to each other in that the same kind of water was obtained from the

same kind of dispenser; one dispenser just had a pendulum in front of it. It thus makes sense to compare the total of the two measures for one animal with the total for the other, yielding a two-to-one ratio for the number of ten-second intervals during which the second animal vs the first "drank" from either source. Since drinking is a basic activity required to sustain life and is regulated within fairly narrow bounds by physiological factors, it seems reasonable to assume that the animals did not differ by a factor of two in the amount actually drunk. It seems more likely that the two animals differed in the amount they drank per response counted by the recording device. It should be recalled what a given number of responses represents: it is the number of ten-second intervals, defined by the interfacing, during which the particular type of behaviour occurred. Whether the animal drank continuously throughout a given interval or for only a fraction of a second, the recorded response was the same. It is quite likely that the second animal took more numerous but shorter drinks than the first; this hypothesis is substantiated by the much lower autocorrelation at short lags for the Capacitance Water for the second animal than for either water measure for the first animal.

The first animal made extensive use of the Wheel, while the second made virtually no use of it. The second animal made substantially more use of the Climber than did the first. The pattern for these two measures is similar to

that of the previous measures. Since both the Wheel and the Climber are related to overall activity, it is tempting to conclude that the second animal was "compensating" for his failure to use the Wheel by climbing more and that if he had used the Wheel he would have climbed less. This conclusion is not warranted however without further evidence. Such evidence could have been obtained by periodically preventing the first animal from using the Wheel and observing whether there was an increase in the amount of climbing (with appropriate controls). It is also quite possible that the larger number of responses for the second animal represents more shorter periods on the Climber without more total time spent on it. It should be mentioned, however, that the Climber was used largely as an access to the top of the frame holding the Wheel so that many of the responses of both animals represent only brief periods of time on the Climber. The Climber was actually quite small for a rat and the animals could climb up it and onto the frame of the Wheel in only a second or so. Ideally the Climber should have been substantially larger so that the animals would have spent more time climbing before reaching the top. If it were the case that the second animal used the Climber more frequently but for shorter periods of time, it is likely that the conditional probability of response on the Climber given previous response on the Climber would be smaller at short lags for the second animal than for the first. This probability is greater for the second animal at

lags of up to two minutes but then the lines cross and the probability is greater for the first animal. Thus these graphs do not shed much light on this question.

The second animal appears to have spent a substantially larger proportion of his time in the Nest Box than did the first. This is not very surprising since the first animal slept elsewhere much more frequently than the second. It will be noted that the second animal's total for the Nest Box is about 44% of the maximum possible (i.e. of the sample size). The comparable figure for the first animal is 34%. Clearly the Nest Box was an important place for both animals.

A comparison of the overall totals for the two animals leaves an impression of the second animal as somewhat restricted in his use of the environment. Even when hungry, he would not eat from the Direct Food dispenser; he generally preferred not to drink from the Water Pendulum dispenser, and he avoided entering the Wheel.

Daily Totals

Figures 1 and 2 present the total number of responses for each variable for each day for the first and second animal respectively. The abscissa of each graph represents days, each day beginning and ending at noon (when the animals were generally inactive). The ordinate represents the total number of responses for the particular variable

and day on a logarithmic scale [$y=a(\log(x+b)-\log(b))$]. These graphs will not be discussed in detail but there are several interesting features to be noted.

One of the most striking features of these graphs is that there are several "holes" in them: places where the number of responses suddenly falls to zero for one or more days. As mentioned previously, several of these instances clearly can be attributed to equipment failures, mostly of timers. There is no indication that any of these correspond to failure of anything to "work" for the animal. The instances which can clearly be attributed to failure of a timer are the Direct Food, Wheel and Urination for the first animal. The drop in the Empty Bar for the first animal almost certainly represents a failure of the animal to respond, since only the switch itself and the interfacing and tape drive were involved, and no difficulty was experienced with any of these. The zero response level on Urination for the second half of the second animal's data is attributable to a broken wire on the elimination grid as discussed previously. The zero response rate on the Lights for the second animal after the third day is difficult to interpret. There was apparently no failure of the apparatus. It is quite possible that this animal pressed the Lights bar until the contingency was thoroughly learned and then abruptly stopped, having "satisfied himself that there was nothing new to learn." The unanalyzed data may shed some light on this possibility: it could be that this

animal had pressed the Lights at a much higher rate when he first learned to press a bar and then gradually decreased his response rate to nearly zero by the first day of data reported here.

Figures 1 and 2 reveal generally quite a bit of variability from day to day with much more for some variables than for others and generally less variability for the second animal than for the first. Since the overall level of responding is quite different for different variables, it is somewhat difficult to compare the day-to-day variability between variables. Comparing absolute differences from day to day for one variable with absolute differences for another variable does not make much sense when the totals differ greatly; a difference of 30 between 50 responses one day and 20 the next for one variable is not the same as a difference of 30 between 500 and 470 for another variable. Comparing ratios of responses can also be misleading; one expects a greater percentage variability between successive small numbers of responses than between successive larger numbers.

The Food Bar and Direct Food for the first animal vary from about 150 to 500 and from 3 to 75 respectively (excluding the "hole" in the latter). The Food Bar for the second animal has a range of about 130 to 1000; however, the 130 is quite outside the normal range of variability and 500 might be considered a "typical" minimum. The overall

impression is certainly one of less variability for the second animal. The variability is quite substantial considering the obvious importance of food to the animals. It will be noted that the two food measures tend to covary negatively for the first animal, suggesting that the two may substitute for each other and that the variability in this animal's food intake may not be as great as the variability in either food measure. This covariation could also account for the difference in variability between the animals since the second did not eat from the Direct Food dispenser.

The two water measures for the first animal vary somewhat more than the Capacitance Water for the second animal (the Water Pendulum being essentially unused). Again the two measures covary negatively over days so that the total of the two water measures for the first animal may not vary more than the Capacitance Water for the second animal.

The variability of the Nest Box for the first animal is quite large - from about 175 to over 7000 - and is much larger than that for the second animal, not too surprisingly since it has already been noted that the first animal often slept in the Wheel. The variability of the Empty Bar for the first animal is also quite large - from zero to 150 responses in a day.

The variability of all four elimination graphs is extremely high and represents substantial changes in sensitivity of the drinkometers and, in the case of the

Defecation graphs, instances where feces stuck to the grid causing repeated recording of Defecation until discovered by the experimenter. Any correlations at lags longer than a few hours will be more a function of the periodicity with which the experimenter checked the apparatus than of the animals' behaviour.

There are certain basic needs of the organism - food, water, rest - and these cannot vary greatly for substantial periods of time. Even if the animal feels "lazy" on a given day, we expect it to eat. Other behaviours are much more a matter of "preference": if the animal does not feel very energetic, why should it run the Wheel? Although it is by no means necessary, one might expect to find greater variability from day to day in unessential activities than in activities associated with basic needs. For the first animal the Nest Box, the two food and two water measures do not appear to vary less than do the Wheel, Climber, and Empty Bar. The second animal used only one source each of food and water and only two unessential variables, the Climber and the Radio. The Climber varied more than did the food or water measures while the Radio varied less, insofar as its smaller numbers are comparable at all. Overall it does not appear that the individual unessential measures varied more from day to day than did the basic measures. It is still possible that the total amounts eaten and drunk might vary less than the unessential variables; however, if the two food and two water measures were aggregated to form

some kind of overall measures, then perhaps the unessential ones should also be aggregated, though how to do this is a more difficult question.

An examination of the graphs for the first animal indicates a general similarity of shape (except for the "holes") of the Direct Food, Water Pendulum, Climber, Wheel and Empty Bar which is not shared by the Food Bar and Capacitance Water. This similarity may be attributable to something like an activity component which one might expect to be shared by the Climber; Wheel; Empty Bar (since it is unessential); the Water Pendulum but not the Capacitance Water (since the former is clearly more effortful than the latter); and the Direct Food but not the Food Bar (since the former involved the effort of biting a piece from a relatively hard food chunk and chewing it, while the pellets associated with the latter were much softer and were obtained with much less effort).

The terms "similarity", "variability", and "covary" have been used above in discussing the series of daily totals, and such terms bring to mind the more precise concepts of variance and correlation. It would certainly be possible to calculate the variance of each total and the correlation of the daily totals for each pair of variables. The number of days is not sufficient, however, to place much confidence in such results, even if the substantial holes did not exist. One would probably want at least 50 days'

data for each animal to make these calculations worthwhile. Reliable estimates of the correlations of the daily totals could be quite informative. If two measures were largely measures of the same underlying motivational component, such as the Food Bar and Direct Food for hunger, one might expect them to be substitutable for each other - to the extent that the animal did one, he would not need to do the other. This would likely lead to a negative correlation of the daily totals. If the correlations of the first measure with most measures irrelevant to the particular motivational component which the two shared were similar to the respective correlations of the second measure with the same variables, our belief in the underlying component would increase greatly. It is quite possible to calculate certain constraints on the magnitude of the various correlations. For example, if the correlations of two measures (say A and B) with the same "other" measure (Q) were both 0•5, the strongest negative correlation they could have with each other would be -0•5 to make the correlation of A and B given Q equal to -1•0. Thus the magnitude of the correlations need not be great, if the pattern fits, in order to make inferences to underlying components. The number of constraints increases very quickly as the number of variables increases.

The "Average" Day

Figures 3 and 4 present the average across all days of the number of times each type of event occurred in each 15-minute interval of the day. The abscissa represents time of the day in 15-minute intervals. The ordinate represents the average number of responses, on a logarithmic scale [$y=a(\log(x+b)-\log(b))$]. These could be described as graphs of what each animal did when in the "average" day. Of course the "average" here, as with the mean of any variable, need not be in any way "typical". Since the ordinate of the graphs is not based on equally spaced intervals but rather is based on a logarithmic scale, a difference of one quarter of an inch of height on the graph might correspond to a difference in number of responses from about 20 near the top of the graph to one half near the bottom.

It will be noted that the size of the fluctuations of some of the variables is quite remarkable - for example the Food Bar for the first animal drops from a mean of almost ten responses during the interval from 2:15 to 2:30 a.m. down to a mean of about one tenth of one response during the interval from 3:00 to 3:15 a.m. Such extreme fluctuations imply that the animal's "biological clock" is quite accurate indeed. In this case the clock is being driven by photoperiodicity (and perhaps other periodicities), but the greatest part of the activity is taking place during the night when light cues will be the least precise and there

is, in any case, considerable variability from day to day attributable to changes in the weather. At this time of year (January and February) and latitude (54 degrees north) the period of daylight was changing fairly quickly. The three dips in the Food Bar for the second animal around 3:30, 5:30 and 8:00 a.m. are particularly striking (note also the similarity to the Capacitance Water).

The regularity from day to day implied by the graphs of Figures 3 and 4 contrasts with the variability from day to day implied by some of the graphs of Figures 1 and 2. These results are not contradictory, however; they indicate that the patterning of responses within days was fairly regular even though the level varied across days.

The extreme dips, and the correspondence between graphs of some peaks and troughs but not others, suggest that, though the patterning of responding is complex, it is not fortuitous. It appears that there are several underlying components, each of which has some temporal patterning, and that two or more of these may contribute to responding on each variable. Thus two graphs will appear similar to the extent that they share underlying components but different to the extent that they do not. This possibility suggests that it may be possible to identify these underlying components by further analyses of the pairwise similarities

of the variables, perhaps through spectral analysis or factor analysis of some derivatives of the raw data variables.

The graphs for the first animal display a distinct peak in activity around 9:00 p.m., followed by a decrease in activity from about 11:00 p.m. to midnight. After midnight the situation is less clear: some graphs show only a jagged broad increase in activity while others, most notably the Food Bar, Direct Food and Empty Bar, show evidence of separate peaks. It appears as if there may be three separate peaks: 2 to 3 a.m., 5 to 7 a.m. and a smaller peak at 8 to 9 a.m. Insofar as the Nest Box is used for resting, one might expect substantial dips in its graph corresponding to peaks in other variables. The fact that this is not the case is likely attributable to the fact that the Nest Box graph could be interpreted as the "sum" of two "underlying" curves, one representing resting and the other representing entering the Nest Box as part of exploratory behaviour. This animal was often seen to enter the Nest Box for periods of only a few seconds during periods of general mobility. It would likely be possible to separate these two opposite tendencies by examining the duration of occupancy. A frequency distribution of durations would probably be bimodal with durations in the range of one to ten minutes almost non-existent. This particular variable might prove a

useful reference for evaluating potential techniques for separating underlying components: the best of these techniques could then be tried on other variables.

The graphs for the second animal show much more activity during the daylight hours than do those for the first animal, not very surprisingly since the second had pigmented eyes and could see perfectly well in bright light while the first lacked pigment and therefore did not see well in bright light. There may, of course, have been other strain differences, sex differences or differences in rearing which contributed to the daylight activity. This animal shows one broad major peak of activity of five to six hours centred about midnight. The afternoon and early evening from about 1:00 to 9:00 p.m. could be considered as including one or two peaks, less well defined and less active. There is also a fairly substantial peak from about 9 to 11 a.m. The similar pattern of steep peaks and troughs in the early morning for the Food Bar and Capacitance Water is very striking. There is some tendency for dips in the Nest Box during the middle of the night and about 9 to 11 a.m. to correspond to peaks in the other variables. The sharp peak in the Nest Box graph at 11 p.m. does not appear to correspond to any of the other graphs.

Calhoun (1963), studying wild-caught rats living outdoors in a colony, suggests that rats show two peaks in activity, one shortly after dusk and one shortly before

dawn. He differentiates these peaks only to the extent that the first is larger than the second. His description does not do justice to the complexity of the graphs just considered, where there are a number of different shaped peaks for different variables. There are, of course, many possible reasons for his simpler description, including the fact that he was observing the aggregate activity of several animals.

Lagged Correlations and Conditional Probabilities

One generally thinks of the correlation between two variables as a symmetric function of these arguments: the correlation of X and Y equals the correlation of Y and X. However, the correlation between two variables as a function of the lag between them is not symmetric about lag zero: in general the correlation between X at time t and Y (different from X) at time t+k is not equal to the correlation between X at time t+k and Y at time t. Therefore the number of distinct lagged simple correlation functions generated by N variables is the square of N: in this case there are 12 variables for each animal and 144 series of lagged correlations. The same case holds for any particular form of partial correlation and for conditional probabilities. In this study, with two animals, twelve variables, simple correlations, one form of partial correlation and one form of conditional probability, there are in principle 864 series of almost 1000 numbers each. However, some of the

variables in this study had almost no responses and therefore variances of approximately zero. These a priori uninteresting series were not graphed, leaving 471 series actually drawn.

Almost 500 series of almost 1000 numbers is still too many to present and discuss. Some fairly drastic form of data reduction is still necessary. There are several possible approaches to this problem; however, all of the rigourous mathematical procedures are very complex and none has been applied to this type of data in order to have had a chance to be found satisfactory. In the absence of any reasonable precedent, the calibrated eyeball was employed to select several "interesting", "representative" graphs for inclusion as Figures 5, 6, 7 and 8. It will be noted that none of the graphs for the second animal has been included: these do not differ systematically from those for the first animal, except that more of them were eliminated for lack of variance before the 471 were drawn. It will be noted also that none of the partial correlations is included. The partial correlations are interestingly different from the simple correlations, but the general differences can be described fairly readily without the need for examples.

There are a number of general features of the graphs in Figures 5, 6, 7, and 8 which should be noted. First, it should be remembered that the time scale of the graphs changes at the dotted vertical lines, becoming more

compressed by factors of 6, 10 and 3 at the three vertical lines respectively. The ordinate is on a logarithmic scale, with negative values being transformed as the negative of the transform of the positive values rather than the transform of the original negative values (which transform does not exist in the real number system). The value on the graph, y (in inches above the abscissa), as a function of the correlation, x, is $y=sgn(x)a(\log(abs(x)+b)-\log(b))$, where a and b are scaling factors which are the same for all of the graphs and sgn(x) is the signum function, which takes the value +1 if $x>0$, 0 if $x=0$ and -1 if $x<0$. Because of these two non-linear transformations, features will become more compressed horizontally in successive sections of each graph representing longer lags and more compressed vertically as distance from the abscissa increases.

It may be seen from some of the correlations that there appear to be definite lower limits which are not equal to minus one. Such limits exist for all the crosscorrelations and correspond to conditional probabilities of zero. Both the correlations and conditional probabilities also have maximum possible values which are generally less than one. In the case where the variables are binary, taking only the values zero or one, and where the number of ones is less than the number of zeros for all variables, as is the case here, formulae for the maxima and minima are relatively simple. Assuming that N is the sample size; that n_1 and n_2 are the number of responses on variables 1 and 2, and for

convenience that $n_1 \leq n_2$, these formulae are:

1) the maximum possible value of the autocorrelations is 1.0
2) the maximum possible value of the crosscorrelation is 1.0 whenever $n_1=n_2$
3) the minimum possible value of the autocorrelation of variable 1 is $-n_1/(N-n_1)$
4) the minimum possible value of the crosscorrelation is $-n_1n_2/\sqrt{N^2n_1n_2-Nn_1^2-Nn_2^2+n_1^2n_2^2}$
5) the maximum possible value of the crosscorrelation of variables 1 and 2 is $(Nn_1-n_1n_2)/\sqrt{N^2n_1n_2-Nn_1n_2^2-Nn_1^2n_2+n_1^2n_2^2}$
6) the maximum possible value of the conditional probability of variable 2 following variable 1 is 1.0
7) the maximum possible value of the conditional probability of variable 1 following variable 2 is n_1/n_2
8) the minimum possible value of all conditional probabilities is 0.0 (since $n_1, n_2 < N/2$).

For any correlation the absolute value of the minimum given in 4) above will be less than the maximum given in 5) above, the ratio of these numbers being $n_2/(N-n_2)$, which will be quite small when n_2 is a small proportion of the sample size. Tables 2, 3 and 4 present the maximum and minimum possible values of the correlations and the maximum possible values of the conditional probabilities respectively, for those variables having a sufficient variance for their graphs to have been drawn. A comparison of Tables 2 and 3

indicates that the maximum possible values of the correlations are generally quite a bit larger than the absolute values of the minimum possible values. A comparison of these two tables with the graphs of Figures 5 and 7 reveals that the correlations often fall to the minimum possible values and even remain there for considerable numbers of lags, whereas the maxima are approached only infrequently, with the exception of the short-lag autocorrelations.

There are also "between-lag" constraints for each correlation or conditional probability function. These are generally more complicated to express and less interpretively significant than is the case for the above results. Among the simpler of these constraints are the facts that the average across lags of the conditional probability is approximately equal to the unconditional probability of the lagging variable, and that the average across lags ~~of~~ a correlation is approximately zero. (The word "approximately" is used instead of a more precise but complicated statement regarding limits at infinity.)

One of the most striking features of these graphs is the very strong periodicity. The periodicity ranges from that of the autocorrelation of the Nest Box, which is very smooth with almost no variability at any period other than 24 hours, to that of graphs such as the autocorrelation of Food Bar, with very complex repeated patterns. It will be

noted also that the correlations generally do not show a gradual decrease over days, suggesting that the underlying processes are genuinely periodic. Correlations such as these would appear to be ideally suited to Spectral Analysis and might be expected to yield clean results without the types of compensating manipulations often required in estimating power spectra (Blackman and Tukey, 1958).

The dominant period in these graphs is clearly 24 hours; however, there are many short-lag components superimposed over the basic frequency. It will be noted that the autocorrelation of the Empty Bar shows a peak not at 24 hours but rather between 22 and 23 hours and that the Wheel shows small troughs within broad peaks at 24 hours and 48 hours.

The information contained in the simple correlations is largely redundant with that contained in the conditional probabilities and one might question the usefulness of calculating both and wonder whether one is uniformly preferable to the other. The correlation is certainly more common in the biological sciences and has some well-known properties. It has a natural zero which corresponds to a lack of relatedness and it takes both positive and negative values which are meaningfully different. To this zero point corresponds the unconditional probability, a point which varies from graph to graph, with conditional probabilities less than the unconditional probability corresponding to

negative correlations. The conditional probability is not symmetric about the unconditional probability the way the correlation is about zero. On the other hand, we have seen for this study that the correlation is not really symmetric about zero in the sense that the absolute value of the minimum possible value is less than the maximum possible value, so that the symmetry is partly an illusion. The lack of symmetry in the conditional probability is even more pronounced when the function is graphed on a logarithmic scale, as is the case here. It is difficult for an individual to compensate mentally for the compression of the conditional probabilities below the unconditional probability.

The correlation, being a moment about the mean, compares the values of a variable to its average value and thus it is possible to compare the correlations of different variables. In the process of doing this information must be discarded which is retained by the conditional probability.

For these and other reasons, it seems preferable to examine both the correlations and the conditional probabilities, pending further experience with this type of data.

Although the extremes reached by many of the series of correlations are not large in absolute value, they should not be judged too small to be of practical significance as quickly as one might so judge a single correlation. The

extent to which activity on one variable during a period of time is predictable from activity on another during a previous period of time may be quite substantial, even if the average value of the correlation is only .01. Unfortunately the correlation coefficients obtained from the same pair of variables at different lags are not independent and so the above type of predictability is not easy to estimate.

Auto-relations

Even the most cursory glance at the graphs of Figures 5 and 6 indicates that there is considerable diversity among them and complexity within some of them. These factors suggest examining each relation individually and therefore a few words will be said about each in turn.

The first few lags of the Food Bar show a pattern very similar to that of a damped harmonic oscillation, such as the displacement of a pendulum which is released and allowed to swing freely subject to considerable friction. The reappearance of similar patterns at various places within the first half-hour of lag suggests that the oscillation may be not only damped but subject to interference from another component of different frequency - analagous to the "beats" produced by two slightly different pitches. The main frequency is produced by the fact that the Food Bar is on an FI-20 second schedule, which should produce repeated

patterns of responding somewhat more than twenty seconds apart (since the animal is reinforced for the first response after twenty seconds have elapsed since a reinforcement). Even though the animal may begin responding less than twenty seconds after the previous reinforcement, the pattern must have a period longer than twenty seconds. The "interfering" frequency does not appear directly on the graphs; it is the sampling frequency of the apparatus. With a period of ten seconds, this frequency is somewhat less than one half the frequency of the behaviour. Had the sampling frequency been on the order of once per second or higher, the interference would not have been produced and the oscillation of the behaviour would have appeared much more strongly. This type of effect demonstrates why the sampling frequency should be kept substantially higher than the frequency of any effect of substantive interest (which the FI-20 schedule is not in this study).

The section of the Food Bar graphs representing lags from one half hour to four hours appears to have two dominant components in addition to the general downward trend, one component with a period of slightly less than one hour and one with a period of about 30 minutes. At lags of greater than four hours these graphs become quite jagged and it is difficult to distinguish periodicities other than 24 hours.

The autocorrelation of the Direct Food shows the "floor" effect of not being able to become more negative than the value of -.003 given by Table 3. The Direct Food graphs are quite spiky with even the 24-hour periodicity difficult to see. There is a tendency for the graphs to fall quickly from lags of zero to about five minutes and then have a hump from about 5 to 15 minutes of lag. There is a substantial rounded peak at about 70 minutes' lag.

The Water Pendulum graphs are similar to those for the Direct Food in several respects: they show the "floor" effect quite clearly; they are very spiky, and they fall quickly from lag zero, this time to about lag three minutes with a very pronounced hump from lags 3 to 13 minutes. The flat minimum from lags of about 19 to $23^1/_2$ minutes results from the fact that out of a total of 1237 "drinks", none was ever followed by further drinking from this source within the period from 19 to $23^1/_2$ minutes later.

The graphs for the Capacitance Water fall very quickly, right to a conditional probability of zero at lag four minutes. Of 1491 "drinks" from the Capacitance Water in 24 days, never was the animal drinking at one time and then again at any time between 4 and $6^1/_2$ minutes later. These graphs are quite spiky with a clear 24-hour periodicity and substantial components with relatively short lags.

After falling a certain amount over the first ten minutes or so of lag, the graphs for the Wheel remain relatively high for lags of up to about one hour. This relatively flat region reflects in part the fact that the animal sometimes ran in the Wheel for long periods of time. It also reflects in part the animal's tendency to enter the Wheel repeatedly during extended periods of activity. It will be recalled that this animal often slept in the Wheel; however, such periods are not included in these graphs since it was turning of the Wheel which was recorded, not mere occupancy. It is interesting that the animal never ran in the Wheel at about three hours after having done so. These graphs show quite distinct peaks at 24 and 48 hours and troughs at 12 and 36 hours. There are also quite substantial lesser components with periods of 4 to 5 hours and 7 to 8 hours. Figure 9 presents the section of the auto-conditional function from lag four hours to lag 48 hours, with the three clearest components sketched in roughly below. There is also a good deal of short-period jaggedness superimposed on these relatively long-period components. With almost 2000 reponses on this variable, it seems reasonable to assume that most of the jaggedness can be attributed to the nature of the animal rather than to sampling error, as might have been the case with, say, the Direct Food which had only 557 responses.

The graphs for the Climber, like those for the Wheel, tend to fall quite quickly from lag zero and then level off

to lags of over an hour, though here the "level" portion is quite jagged and not much above a conditional probability of zero. At longer lags, these graphs look very jagged with only the 24-hour periodicity reasonably easy to distinguish.

The graphs for the Nest Box remain very high for a large number of lags and are extremely smooth compared to all the others. It will be noted that at longer lags the troughs are wider than the peaks: i.e. the graphs are negative at more than half the lags within each cycle. The significance of this fact is not clear: on the one hand it is tempting to attribute some characteristic to the animal, but on the other hand, the graph cannot become more negative than the value of -.507 given in Table 3, whereas it does become more positive than +.507, and the average over all lags must be approximately zero. Although the animal tended to remain in the Nest Box for long periods of time, it also entered the Nest Box for short "exploratory" periods of time during periods of peak activity. These short duration entries result in a distinct drop in the graphs over the first 2 or 3 lags. This drop is not visible with the degree of reduction used to produce Figures 5 and 6 , but was quite clear in the original graphs drawn about three times larger.

The graphs of the Empty Bar drop very quickly over the first three lags and then very slowly to lags of almost an hour. There is a substantial peak at lags of about 3 to 4 hours and another at lags of 22 to 23 hours, with relatively

low levels in the vicinity of 24 hours of lag. It is difficult to interpret this latter peak, but the peaks near multiples of 24 hours suggest that there is likely a component at a period of approximately 24 hours, with another component which is interfering with it. If the period were really 22 to 23 hours, one would expect peaks at 2,3,...,8 times that period, rather than at 2 to 8 days. The eighth peak would occur several hours before the lag of eight days. The interfering frequency could well be that represented by the peak at 3 to 4 hours.

Groups of Auto-relations. We have seen that the graphs of Figures 5 and 6 are complex and diverse, with some repetition of similar patterns within graphs. The question which now comes to mind is: are there any similarities between graphs, other than the 24-hour periodicity, which would allow any further organization and interpretation of the variables? It might be anticipated that the a priori pairs - the two food variables, the two waters and the Wheel/Climber pair - should display some similarities and it would not be surprising if other groupings showed similarities indicative of common underlying components.

The graphs of the two food variables could hardly be considered as strikingly similar. This lack of similarity may be partly attributable to the fact that the overall response levels of the two variables are very different, putting them on different scales on the graphs and making

the Direct Food appear more irregular through sampling error. It may be that a more sensitive analysis would detect similarities of the two variables, or that their relations with each other or with other variables will bring out similarities.

The graphs for the two water variables both fall very quickly over the first dozen lags. They also have peaks in the region of lags of 17 to 19 minutes and 25 to 26 minutes. The hump in the graphs of the Water Pendulum at about 5 to 15 minutes does not correspond to a similar feature of the Capacitance Water. At longer lags both are quite spiky and it is difficult to discern any particular similarities. It would appear that this animal tended to have a drink, do something else and not drink (i.e. a conditional probability less than the unconditional probability), have a second drink, and do something else again.

The "activity" measures, the Wheel and Climber, both remain relatively flat from lags of a few minutes to about an hour. They share this attribute with the Empty Bar, suggesting that this plateau may represent some common underlying component not found in any of the other variables. This could be an "activity" or "exploratory" component. It might be anticipated that such a component would show up as a broad but not very high plateau, as the animal tended to move around the cage engaging in a number of different activities instead of staying with any one for

very long. One might expect a general activity component to show up in a wide variety of different behaviours and, if this is such a component, it is interesting that it appears in only three measures. However, the food and water variables are of a special and related nature, while the Nest Box has such a strong tendency to recur at all lags up to several hours that the plateau may be masked rather than absent. At lags of more than an hour the jaggedness of these three graphs makes it difficult to discern similarities other than the 24-hour periodicity.

The Direct Food and Water Pendulum graphs show a hump at about 5 to 15 minutes of lag which they do not share with any other variables. These are both the more effortful and less frequent of their respective pairs. This is the only discernible feature that these graphs share with each other and not with most of the other variables. It is difficult to imagine what underlying component it might be that these two variables share only with each other and that increases the tendency to respond at lags of up to 15 minutes following a previous response. Perhaps the cross-relations will shed some light on the problem.

Cross-relations

Properties. In the case of the auto-relations, each point represents the relation of a variable to itself at a different lag and it makes no sense to "reverse" the lag.

However, in the case of the cross-relations it makes sense to consider each variable both leading and lagging the other. Thus the graphs may be paired such that each pair involves the same pair of variables but differs in terms of which leads and which lags. In the case of the conditional probabilities these graphs vary around the unconditional probability of the lagging variable, and it is not meaningful to compare the members of each pair with respect to the strength of the relation at any given lag. The standardization involved in calculating the correlations guarantees that the two graphs will occupy about the same range (cf. the symmetry of the matrices in Tables 2 and 3), and indeed that the lag-zero correlations of each pair of graphs are identical. It is therefore possible to "flip" one of each pair about the ordinate and make one graph with the lag of zero in the centre of the abscissa with both positive and negative lags. Figure 7 was produced in this way. It is of course arbitrary which graph is flipped as long as the appropriate lags become negative.

In the graphs of the auto-relations we expect a periodicity of period p to appear as a peak at lags p, 2p, etc., because each graph starts with a peak at lag zero. In the graphs of the cross-relations, however, the first peak of a component with period p may occur at any lag less than p, say lag k, and then reappear, unless it is masked by some other component, at lags $np+k$, for all $n=1,2,3\ldots$. Thus a component with period 24 hours which first appears at lag 16

hours, as in the Nest Box following Capacitance Water (Figure 10), reappears at lags of 40 hours, 64 hours, etc.

If two graphs are combined into one as suggested above, one expects any periodicity to be continuous throughout. Thus if there is a component with period p in one of the original graphs, we expect it to occur throughout the combined graph. This means that if the first peak to the right of the origin occurs at lag k, then there should also be a peak at lag -(p-k) in order for the periodicity to be maintained across the origin. Additional peaks will occur at all lags -(np-k), for n=1,2,•••. Figure 10 d) illustrates this nicely for a period of 24 hours. It will also be noted that, in order for the peaks to be of similar shape in the combined graph, the corresponding peaks must be mirror images of each other in the original graphs.

Particulars. The first two graphs of Figure 7 represent the most typical form of crosscorrelation found in the results of this study, where the correlation is positive at relatively short lags on both sides of lag zero, but at very short lags drops quite sharply. The first graph, Food Bar leading Wheel, goes negative within a broad band of suppression more than ten minutes wide. Both of the corresponding autocorrelations remain relatively high for a substantial number of lags. The second graph, Wheel leading Climber, goes only slightly below zero in a band of suppression only about two minutes wide. As might be

expected, the autocorrelation of the Climber drops much more quickly than does that of the Food Bar.

The third graph of Figure 7, Water Pendulum leading Capacitance Water, shows the case where the correlation is negative at all relatively short lags and does not change appreciably very near lag zero. Because both measures represent drinking and can presumably be substituted for each other, it is not surprising that they are negatively correlated at all relatively short lags since we have already seen from the autocorrelations that the animal tended to drink for a while and then not drink again for a few minutes.

The fourth graph, Food Bar leading Direct Food, presents a somewhat ambiguous case. The smoothness of the trough near lag zero fits well with the general rates of curvature in adjoining regions, suggesting that this trough may represent a relationship between underlying tendencies rather than a suppression effect. It will be noted that the trough is wider to the positive side of zero than to the negative side, as would be anticipated of a suppression region where the leading variable has an autocorrelation which stays high longer than does that of the lagging variable, as is the case here. It will be noted also that both of the measures represent eating behaviour just as both in the last graph represented drinking. The broad region of negative correlation found at short lags in that graph is

not present here, even though the two methods of obtaining food can be substituted for each other. The difference here presumably corresponds to the fact that the animal drank in discrete bouts with periods of zero probability of drinking in between, whereas she was fairly likely to eat at any relatively short lag after eating, as witnessed by the positive autocorrelations of the food measures at almost all relatively short lags.

The fifth graph of Figure 7, Food Bar leading Empty Bar, shows only a very slight drop near lag zero in a generally smooth crossing of the ordinate. This pattern is not typical of many of the crosscorrelations. It will be noted that the autocorrelation of the Empty Bar drops very quickly from lag zero. Further, it was noted that the animal tended to press the Empty Bar when it was generally very active and so likely to engage in a number of different behaviours in close temporal proximity. The Empty Bar is unique in that most of its responses seem to fit this general pattern. Insofar as there is any suppression at all near lag zero, we would expect it to be predominantly to the right of lag zero, since the Food Bar had a substantial autocorrelation. A close examination of this graph indicates that this is the case.

The sixth graph of Figure 7, Direct Food leading Empty Bar, shows the exact opposite of the typical pattern exemplified by the first two: a sharp rise around lag zero. This peak cannot be attributed solely to the peculiar character of the Empty Bar described above, since other graphs involving the Empty Bar, including that discussed above, do not show this peak. It is clear that the tendencies of the Empty Bar and the Direct Food are high simultaneously, and what is more, that the behaviours mutually facilitate each other at lags as short as ten seconds. Even in this case there must be a suppression effect at sufficiently short lags since at least three to four seconds were required for the animal to get from one piece of apparatus to the other. A higher sampling frequency therefore would have resulted in a very steep drop at lags of less than four seconds.

None of the graphs of Figure 7 appears to be very close to symmetric about lag zero; nor does any on visual inspection appear to be entirely periodic. There are probably components which are periodic and which are symmetric, but the graphs are too complex for these to be seen readily. Some of the crosscorrelations are simpler than these, particularly those involving the Nest Box which has a very smooth autocorrelation apparently involving only two components of very unequal magnitude. The crosscorrelations of the Nest Box with other variables tend to be clearly periodic but not symmetric. Figure 10 a)

shows the two graphs of Capacitance Water both leading and lagging Nest Box, superimposed, aligned along both axes. The peaks and troughs occur at different lags in the two graphs. Figure 10 b) shows the two longer lag sections of the Nest Box leading Capacitance Water graph separated and individually superimposed over the Capacitance Water leading Nest Box graph so as to optimize the fit. Note that the peaks and troughs of the two graphs are quite different in shape. Figure 10 c) presents the same sections of the Nest Box leading Capacitance Water graph in mirror image and similarly aligned. The fit here is much better. The first peak of the Nest Box leading graph occurs at a lag of about 8 hours, while the first peak of the Capacitance Water leading graph occurs at a lag of about 16 hours. The sum of these lags is 24 hours (the lag between successive peaks in each of the graphs), indicating that the combined graph will be periodic across lag zero. The combined graph is presented as Figure 10 d).

Although pairs of conditional probability graphs cannot be joined to make continuous graphs, they do have certain very attractive features. The full formula for the conditional probability of any one of a group of events following at a certain lag after any one of a second group, does not encourage estimation for groups of more than two types of events. However, if the lag-zero probabilities of co-occurence are approximately zero within both groups, the formulae simplify considerably. It is then necessary only

to sum the probabilities of each event in the later group following each event in the earlier group at that lag. Thus the probability of drinking from either the Water Pendulum or the Capacitance Water at a lag of 10 minutes after eating from either the Food Bar or the Direct Food is approximately equal to a sum of only four numbers: $P_{10}(FB,WP)+P_{10}(DF,WP)+P_{10}(FB,CW)+P_{10}(DF,CW)$. It is also possible to answer questions such as: "what does the animal tend to do after x", where x may be a group of events, in terms of comparing the probabilities across variables or compound variables such as "eating". The sum of all these probabilities of mutually exclusive events at a given lag must be less than or equal to 1 under the restrictions imposed.

Figure 8 presents several of the conditional probability graphs of cross-relations for comparison with those of Figure 7.

We have seen from the graphs of Direct Food with Empty Bar in Figures 7 and 8 that the tendency against "simultaneous" events of different types is by no means universal. The strength of this positive relation is difficult to perceive from the graphs. The lag-zero correlation of Direct Food and Empty Bar is about +0·35. The lag-zero conditional probability of Empty Bar given Direct Food is greater than 0·4. This means that of 557 ten-second intervals during which the animal ate from the

Direct Food, it also pressed the Empty Bar during about 225 intervals. This is a very substantial number considering the low overall response rate on the Empty Bar and considering that the two pieces of apparatus were at opposite ends of the cage. If one were to make the admittedly unreasonable assumption of independent Bernoulli trials, the number of joint occurences of the two events should be approximately equal to the product of the sample size, the unconditional probability of the Direct Food and the unconditional probability of the Empty Bar or about $207360 \times .003 \times .004 \cong 24$. The impossibility of truly simultaneous events, together with the distance between the two pieces of apparatus, would tend to make this number even smaller. The animal clearly had a fairly strong tendency to engage in these two behaviours in close temporal proximity. This tendency drops quite quickly with time, to about 44 occurences with an interval of 20 seconds in between.

It is clear from the graphs presented that the temporal patterning of the behaviour of the animal is both strong and complex, involving various periods other than 24 hours. It is also clear from the displacement of the peaks from one graph to another that even the 24-hour periodicities do not represent a simple 24-hour activity cycle: different behaviours peak reliably at different lags with respect to each other. This observation serves to confirm the same conclusion drawn from an examination of the "average" day.

Partial Correlations. The graphs of Figures 7 and 8 demonstrate very complex patterning. It is clear that there are substantial regular components but how many and what they are like cannot be ascertained by mere inspection of the graphs. Further analysis requires some form of decomposition. As discussed previously, one impediment to such a decomposition involves a suppression effect at short lags. This could be overcome, and studied as a phenomenon in its own right, if it were possible to interpolate the values of the cross-relations at short lags. Most common methods of interpolation will not be applicable to this situation. One possible approach to the problem involves the calculation of the partial correlations mentioned in the Data Collection and Analysis section. The partial correlations have the advantages that they are familiar to behavioural scientists and have well-known properties. The calculations can be applied to the entirety of a series, rather than requiring an arbitrary choice of what will be considered "short" vs "long" lags.

As might be expected, when the simple correlations are negative at short lags, the corresponding partial correlations are more positive and the two series converge at longer lags. How much more positive the partial correlation is, and how many lags are required for convergence, vary from graph to graph. The partial

correlations might be taken to represent more nearly the underlying tendency to engage in behaviours when the execution of one behaviour suppresses another. However, there are interpretive difficulties involved with any particular choice of "correction" for the correlations, and until further investigation it seems wise only to note that there are predictable differences in the resulting graphs.

This general pattern for the simple and partial correlations was quite typical but by no means universal. A number of the partial correlations are essentially identical to the corresponding simple correlations from lag 1. As already stated, not all the simple correlations were negative at short lags. The correlation of the Empty Bar with previous Direct Food begins about +0·3 while the corresponding partial starts substantially negative. The correlation of the Empty Bar with subsequent Direct Food is also interesting: here both simple and partial correlations start positive and the partial correlation becomes negative at lags of about 5 to 15 minutes while the simple correlation remains positive throughout. The correlations of the Nest Box followed by Direct Food, Water Pendulum, Wheel, Climber and Empty Bar all fit the general pattern above; however, in each case the simple correlation remains quite flat for lags up to at least 15 minutes, while each of the partial correlations varies quite a bit in the interval from lag 10 seconds to lag 15 minutes, being sometimes very

close to the simple correlation and sometimes greater than zero. There are also a few simple/partial correlation pairs which differ substantially for short intervals at long lags (over 15 minutes).

DISCUSSION

As is clear from the Introduction, this study does not follow from any particular line of previous research. It is related indirectly to a number of other endeavours. Some time will be spent here in an effort to integrate this study with related work.

Relationship to Other Research

Although the rat has been widely used as a subject in psychological research, it has not been the subject of a great deal of research. It has most often been used as a convenient subject with the hope that the results obtained would generalize to other animals, especially man. Much of the early literature relevant to the rat is summarized by Barnett (1963). Some of this early work is relevant to the current study and is still worth reading.

Wang (1923) found a very strong four-day periodicity in the wheel-running of female albino rats. The periodicity corresponded to the independently assessed oestrous cycle. The results of the present study are somewhat ambiguous on this matter because the failure of a timer connected to the Wheel went unnoticed for several days. Inspection of Figure 1 suggests that there may be a four-day cycle but it is much weaker than that obtained by Wang, who found that the one day of maximum wheel-running out of four accounted for more revolutions than the total of the other three, typically

some thousands of revolutions. The autocorrelation of the Wheel in the present study does not show a peak at a lag of four days, not surprisingly with eight days' data missing. Wang's animals were kept in very small cages with ad lib. access to activity wheels. The fact that there was barely room to turn around in the cages probably accounts for the very large number of revolutions per day.

Although wheel-running is the only behaviour studied by Wang, she draws conclusions concerning "spontaneous activity". If wheel-running were typical of spontaneous activity, one might expect to find a four-day periodicity in some of the behaviours in the present study which do not suffer from incomplete data, especially the Climber and Empty Bar, both of which appear to be related to general activity. The daily totals for the Climber are compatible with the idea of a tendency to a periodicity of about four days: the same days which are high for the Wheel tend to be high for the Climber, but hardly strikingly so. The autocorrelation of the Climber at a lag of about four days is somewhat higher than at other multiples of 24 hours, but again not strikingly so. All other variables, including the Empty Bar, show no tendency to a corresponding four-day cycle in either the daily totals or the lagged correlations. If there is any four-day periodicity in the present results, it could hardly be considered to be in general "spontaneous activity".

Richter (1927) reviews a number of studies related to periodicity conducted in his laboratory. He reports that rats allowed to feed ad lib. show a three to four hour cycle in eating and that the maximum probability of eating coincides with the maximum levels of general activity as measured by vibration of the animal's cage. Richter used a small, bare living cage with an independently suspended eating compartment. The autocorrelation of the Food Bar in the present study does show a peak from about four to five hours of lag, but this peak is not large and does not recur at about nine hours as one would expect from Richter's claim that the pattern is periodic. In fact, the peak in the present study looks more like the last of a series spaced about an hour apart. The autocorrelation of Direct Food shows a clear peak centred at a lag of about 70 minutes but nothing significant in the range of three to five hours. The correlation of Food Bar with Wheel is high at relatively short lags, as we have seen, corresponding to Richter's finding that eating coincides with maximum general activity. The other correlations of food measures with activity measures are less clear in their relation to Richter's contention.

Siegel (1961) measured the food intake each hour throughout the day of albino rats allowed to feed ad lib. and kept on a natural light/dark cycle. He found that food intake peaked about 8:00 p.m. and again about 3:00 a.m., the peaks not being different otherwise. His graphs do not

correspond to the "average" day results for either of the animals in the present study. As in the other studies reviewed above, Siegel's animals were kept in quite small cages without much variety of apparatus available.

The above studies all housed albino rats indoors individually in small cages, although they were somewhat more naturalistic than many others in that the animals were kept on a natural 24-hour light/dark cycle. Calhoun (1963) represents a much more naturalistic approach. He kept a colony of wild-caught rats and their offspring in a large outdoor pen. Most of his results are not applicable to the present study; however, he reports a general two-peaked 24-hour activity cycle, with the first, more concentrated peak just after sunset, and the second, more diffuse peak just before sunrise. These results do not correspond with the "average" day of either animal in the present study, or with Siegel's results cited above. Calhoun was observing the aggregate activity of several animals interacting with each other, and these or other differences in methodology may account for the different results.

Kavanau (1963) made a significant advance in continuous, automatic recording of a number of activities of a captive animal. He kept white-footed deer mice in cages equipped with numerous relays, etc. connected to counters and event recorders. His recording apparatus seems somewhat primitive compared to state-of-the-art 15 years later -

digital electronics and machine-readable records - but it was quite an advance over sitting and watching the animal for hours or being restricted to very few behaviours, such as bar-pressing. The elimination grid used in the present study was an elaboration of one reported by Kavanau. His animals faced highly structured contingencies for gaining access to food, nest box, etc. He typically kept animals on any particular contingency schedule for only a few days out of a period of less than a month in the experimental enclosure. Under these conditions, it is unlikely that they established stable temporal patterning and Kavanau's analyses would not have done much to elucidate such patterning if it was there.

With the exception of Calhoun's study, the present study could be seen as extending a trend toward increased automation in data collection, increased sophistication in the analysis of results, and increased freedom and complexity in the animal's environment. Calhoun's study is in a somewhat different tradition, though it can be compared to the others in more ways than warrant mention here.

Further Analysis

We have seen that the temporal patterning of the behaviour of a rat is quite complex, more so than had been anticipated. This complexity makes it very difficult to extract much information from a visual inspection of lagged

correlation and conditional probability functions. There is a need for analytical tools which will decompose these complex functions into simpler constituents in some fairly natural way, much the way the analysis of variance allows us to decompose the variance of a measure into parts attributable to various "independent variables". In this case there are no independent variables in the same sense as in the analysis of variance, and there are several "dependent variables". This situation therefore corresponds more closely to that of factor analysis than to that of the analysis of variance.

It would seem desirable to be able to decompose the results of this study into "simple" periodic, cyclic, and aperiodic components. One way to begin this process would be to estimate a periodic function which contained all the periodic components of the original function and then subtract this periodic function from the original to obtain a function with only cyclic and aperiodic components. If the cyclic components of this function can be estimated, subtraction will yield the aperiodic components.

How to perform this decomposition in the general case is a major problem. However, an inspection of the results of the present study indicates that there are characteristics which may simplify the task. At long lags, say 24 hours or more, it appears that most of the variability is periodic. Lags of 24 hours to eight days can

therefore be used to estimate a periodic function which can then be used to interpolate values at shorter lags. One approach to this estimation would involve averaging the successive values 24 hours apart and substituting the averages for the appropriate lags near zero. This procedure is simple and straightforward but implies some assumptions which may not hold. It assumes that all the periodicities present go through a whole number of periods in 24 hours. Any period greater than 24 hours will add only error, as will any period shorter than 24 hours which does not fit exactly once, twice, ..., n times into 24 hours. It would be possible to repeat this procedure for periods other than 24 hours which were assumed to be present in the data. This procedure would likely work quite well for some of the lagged relations found in this study; however, others may be too complex for such a method.

The above procedure can be generalized quite nicely by taking the Fourier transform of the correlation (or conditional probability) function. The Fourier transform takes a function in the time (lag) domain into the frequency domain. The original function need not be periodic and there is no loss of information: the transformation can be inverted to yield the original function. If a smooth periodic function is transformed, the resulting "spectrum" generally will not be smooth but rather will have sharp peaks at frequencies corresponding to the periods of the original function. This spectrum could then be used to

indicate which periods should be used for the procedure outlined in the previous paragraph. The Fourier transform can also be used directly to generate values for interpolation.

It will be noted that the Fourier transform is not only useful for purposes of interpolation; it can be used to yield a decomposition of a periodic function into components of various frequencies, together with the magnitude associated with each frequency. The Fourier transformation can yield more than the magnitude associated with various frequencies. When two variables are analyzed jointly, the information available includes the frequency composition of each, the phase (lag) relationship at each frequency, and the strength of association at each frequency. Procedures yielding this information are generally referred to as Spectral Analysis.

As indicated previously, the Fourier transform of an aperiodic function exists and contains all the information of the original function. Aperiodic components will be transformed into several (perhaps many) periodic components which when combined cancel each other so as to recreate the aperiodic component. When only the periodic components of a mixed function are desired, all the frequencies which are required under the transformation to make up the aperiodic component can be considered as spurious to the true periodic components. Under the Fourier transformation, non-periodic

cyclic components will also generate frequencies which do not correspond to their period, but rather go to make up the difference between the actual cyclic function and the periodic function having the same period. These and other estimation problems make Spectral Analysis a somewhat touchy business. It is probably worth the effort to apply these techniques to behavioural data, but the special complexities mean that it will be necessary to gain some experience with the techniques before much confidence can be placed in the results. Long series of observations, such as those obtained in the present study, would seem highly advisable for initial attempts at such analysis.

There are other ways to decompose the observed relations. One of these, as we have seen, involves the calculation of partial correlations in order to "remove" the effects of the autocorrelations. There are other possible forms of partial correlation which might yield worthwhile information. It would also be possible to perform a Spectral Analysis of the partial correlations.

Another way to "remove" certain effects caused by the tendency to repeat the same behaviour would be to calculate "transition" variables from the raw data. The transition variable takes the value 1 only if the behaviour occurs in the current interval and did not occur in the previous interval. Analysis of such variables would indicate only the relations with respect to when the animal began various

activities, and would yield simpler relations with generally higher, narrower peaks in the lagged correlations and conditional probabilities. The lag zero autocorrelation will always be 1.0 as in the original analysis, while the lag one autocorrelation will always fall to the minimum value possible given the total number of occurrences on the transformed data variable. Any analysis performed on the raw data could also be performed on these transition variables.

Conclusion

This study is not really a complete entity, but not simply because the data require further analysis and there are some missing data resulting from unreliable apparatus. The approach taken here is quite unconventional in terms of its philosophy of science, its methodology and its analysis. This study is most appropriately viewed as a very preliminary attempt to head in a somewhat different direction from mainstream Psychology: as a kind of pilot study for a new paradigm.

The context of this study included a commitment to an inductive method rather than an a priori, deductive model - a commitment to "give the data precedence" - and a preference for studying the ongoing behaviour of an animal in a familiar environment with a reasonable variety of activities available. Within this context, the aim was to

use the information available in multiple time series to provide:

1) a means of describing the behaviour of the animal in relatively compact terms - both a simple distribution of types of activity over time (the daily totals and the "average" day) and also the sequential patterning of various activities related to each other (the lagged correlations and conditional probabilities).

2) some means of making inferences to underlying constructs which could then be elaborated and tested.

In contrast both to traditional views and also to the current social science fashion of positing causal models and then fitting them by such procedures as path analysis, it was suggested that the asymmetry of lag in time series analyses might allow inference to asymmetric influence relationships (or "causes) from the data, without specific prior models.

It comes as no surprise that this study falls somewhat short of attaining these ambitious aims. The results do, however, serve to confirm that there is a great deal of regularity which can be uncovered by time series analysis, but the regularities are found to be very complex even in the case of the deliberately-chosen "simple" variables included in this study. It does not seem terribly rash to suggest that the effort required to develop this approach further has a high probability of substantial payoff. The propensity of social scientists to speak in terms of causes,

coupled with the inability of most of their methods of analysis to ascribe cause, suggests that the analysis of asymmetric, aperiodic, lagged relations might prove particularly fruitful.

TABLE 1

Total Number of Responses and Average Number of Responses per Day for Each Variable and Each Animal

Variable	First Animal		Second Animal	
	Total Responses	Daily Average	Total Responses	Daily Average
Food Bar	6550	272.9	12449	691.6
Direct Food	557	23.2	4	0.2
Water Pendulum	1237	51.5	7	0.4
Capacitance Water	1491	62.1	4118	228.8
Wheel	1885	78.5	12	0.7
Climber	1019	42.5	1113	61.8
Lights	23	1.0	23	1.3
Radio	0	0.0	50	2.8
Nest Box	69735	2905.6	68686	3815.9
Empty Bar	876	36.5	0	0.0
Urination	10914	454.7	7896	438.7
Defecation	5010	208.8	14349	797.2
Sample Size	207360	8640	155520	8640

TABLE 2

Maximum Possible Values of Lagged Correlations

a) First Animal

Variable	FB	DF	WP	CW	W	C	NB	EB	U	D
Food Bar (FB)	1.0	0.287	0.429	0.471	0.530	0.389	0.254	0.361	0.766	0.871
Direct Food (DF)	0.287	1.0	0.670	0.610	0.542	0.739	0.073	0.797	0.220	0.330
Water Pendulum (WP)	0.429	0.670	1.0	0.910	0.809	0.907	0.109	0.841	0.329	0.492
Capacitance Water (CW)	0.471	0.610	0.910	1.0	0.889	0.826	0.120	0.765	0.361	0.541
Wheel (W)	0.530	0.542	0.809	0.889	1.0	0.734	0.135	0.680	0.406	0.609
Climber (C)	0.389	0.739	0.907	0.826	0.734	1.0	0.099	0.927	0.298	0.447
Nest Box (NB)	0.254	0.073	0.109	0.120	0.135	0.099	1.0	0.092	0.331	0.221
Empty Bar (EB)	0.361	0.797	0.841	0.765	0.680	0.927	0.092	1.0	0.276	0.414
Urination (U)	0.766	0.220	0.329	0.361	0.406	0.298	0.331	0.276	1.0	0.668
Defecation (D)	0.871	0.330	0.429	0.541	0.609	0.447	0.221	0.414	0.668	1.0

TABLE 2 (continued)

b) Second Animal

Variable	FB	CW	C	NB	U	D
Food Bar (FB)	1.0	0.559	0.288	0.332	0.784	0.925
Capacitance Water (CW)	0.559	1.0	0.515	0.185	0.713	0.517
Climber (C)	0.288	0.515	1.0	0.095	0.367	0.266
Nest Box (NB)	0.332	0.185	0.095	1.0	0.260	0.358
Urination (U)	0.784	0.713	0.367	0.260	1.0	0.725
Defecation (D)	0.925	0.517	0.266	0.358	0.725	1.0

TABLE 3

Absolute Values of Minimum Possible Values of Lagged Correlations

a) First Animal

Variable	FB	DF	WP	CW	W	C	NB	EB	U	D
Food Bar (FB)	0.033	0.009	0.014	0.015	0.017	0.013	0.129	0.012	0.043	0.028
Direct Food (DF)	0.009	0.003	0.004	0.004	0.005	0.004	0.037	0.003	0.012	0.008
Water Pendulum (WP)	0.014	0.004	0.006	0.007	0.007	0.005	0.055	0.005	0.018	0.012
Capacitance Water (CW)	0.015	0.004	0.007	0.007	0.008	0.006	0.061	0.006	0.020	0.013
Wheel (W)	0.017	0.005	0.007	0.008	0.009	0.007	0.068	0.006	0.023	0.015
Climber (C)	0.013	0.004	0.005	0.006	0.007	0.005	0.050	0.005	0.017	0.011
Nest Box (NB)	0.129	0.037	0.055	0.061	0.068	0.050	0.507	0.046	0.168	0.112
Empty Bar (EB)	0.012	0.003	0.005	0.006	0.006	0.005	0.046	0.004	0.015	0.010
Urination (U)	0.043	0.012	0.018	0.020	0.023	0.017	0.168	0.015	0.056	0.037
Defecation (D)	0.028	0.008	0.012	0.013	0.015	0.011	0.112	0.010	0.037	0.025

TABLE 3 (continued)

b) Second Animal

Variable	FB	CW	C	NB	U	D
Food Bar (FB)	0.807	0.049	0.025	0.262	0.068	0.094
Capacitance Water (CW)	0.049	0.027	0.014	0.147	0.038	0.053
Climber (C)	0.025	0.014	0.007	0.076	0.020	0.027
Nest Box (NB)	0.262	0.147	0.076	0.791	0.206	0.284
Urination (U)	0.068	0.038	0.020	0.206	0.053	0.074
Defecation (D)	0.094	0.053	0.027	0.284	0.074	0.102

TABLE 4

Maximum Possible Value of Conditional Probability of Row Variable Following Column Variable

a) First Animal

Variable	FB	DF	WP	CW	W	C	NB	EB	U	D
Food Bar (FB)	1.0	0.085	0.189	0.228	0.288	0.156	1.0	0.134	1.0	0.765
Direct Food (DF)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Water Pendulum (WP)	1.0	0.450	1.0	1.0	1.0	0.824	1.0	0.708	1.0	1.0
Capacitance Water (CW)	1.0	0.374	0.830	1.0	1.0	0.683	1.0	0.588	1.0	1.0
Wheel (W)	1.0	0.295	0.656	0.791	1.0	0.541	1.0	0.465	1.0	1.0
Climber (C)	1.0	0.547	1.0	1.0	1.0	1.0	1.0	0.860	1.0	1.0
Nest Box (NB)	0.094	0.008	0.018	0.021	0.027	0.015	1.0	0.013	0.157	0.072
Empty Bar (EB)	1.0	0.636	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Urination (U)	0.600	0.051	0.113	0.137	0.173	0.093	1.0	0.080	1.0	0.459
Defecation (D)	1.0	0.111	0.247	0.298	0.376	0.203	1.0	0.175	1.0	1.0

TABLE 4 (continued)

b) Second Animal

Variable	FB	CW	C	NB	U	D
Food Bar (FB)	1.0	0.331	0.089	1.0	0.634	1.0
Capacitance Water (CW)	1.0	1.0	0.270	1.0	1.0	1.0
Climber (C)	1.0	1.0	1.0	1.0	1.0	1.0
Nest Box (NB)	0.181	0.060	0.016	1.0	0.115	0.209
Urination (U)	1.0	0.522	0.141	1.0	1.0	1.0
Defecation (D)	0.868	0.287	0.078	1.0	0.550	1.0

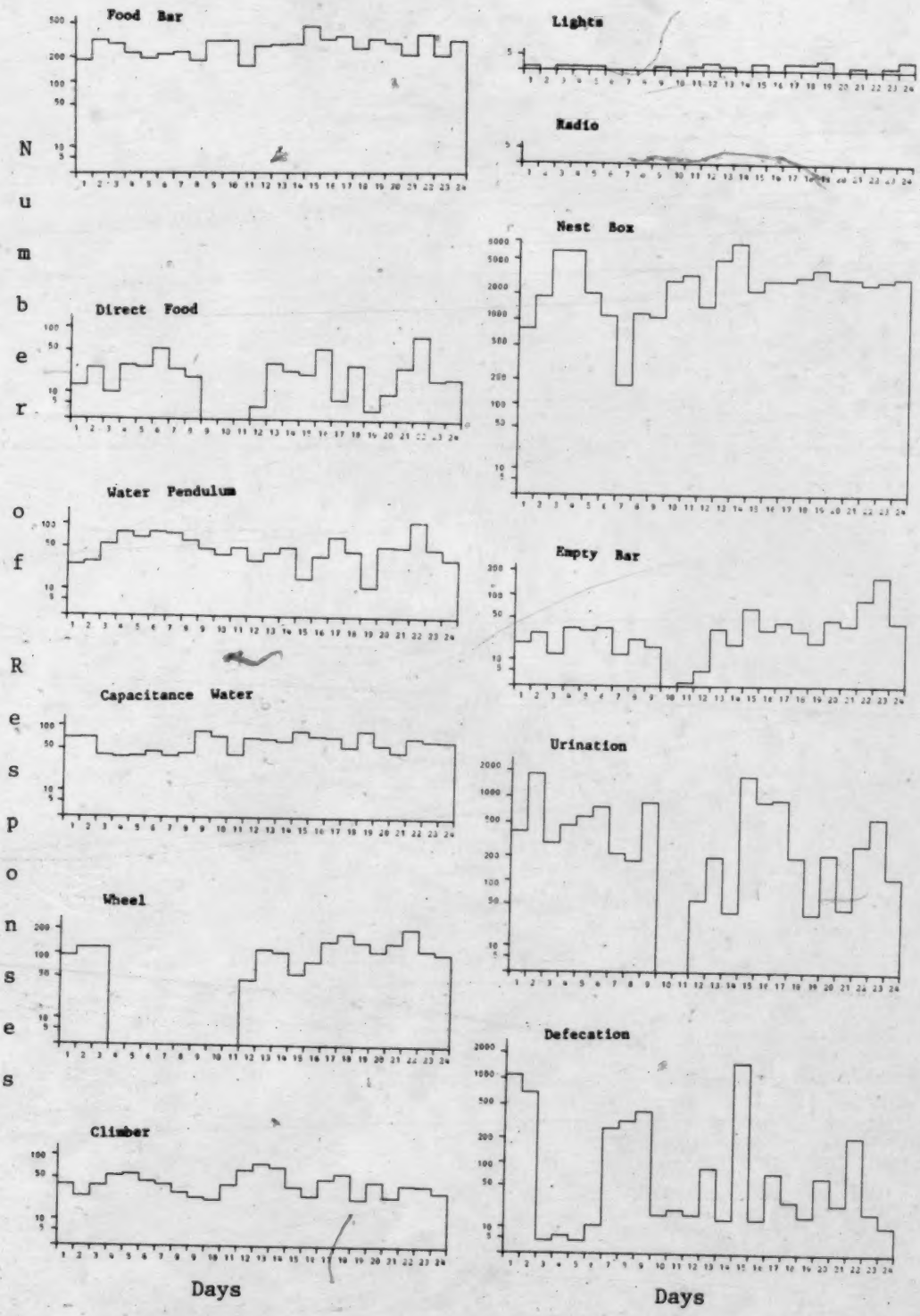

Figure 1. Daily total number of responses made by first animal on each variable.

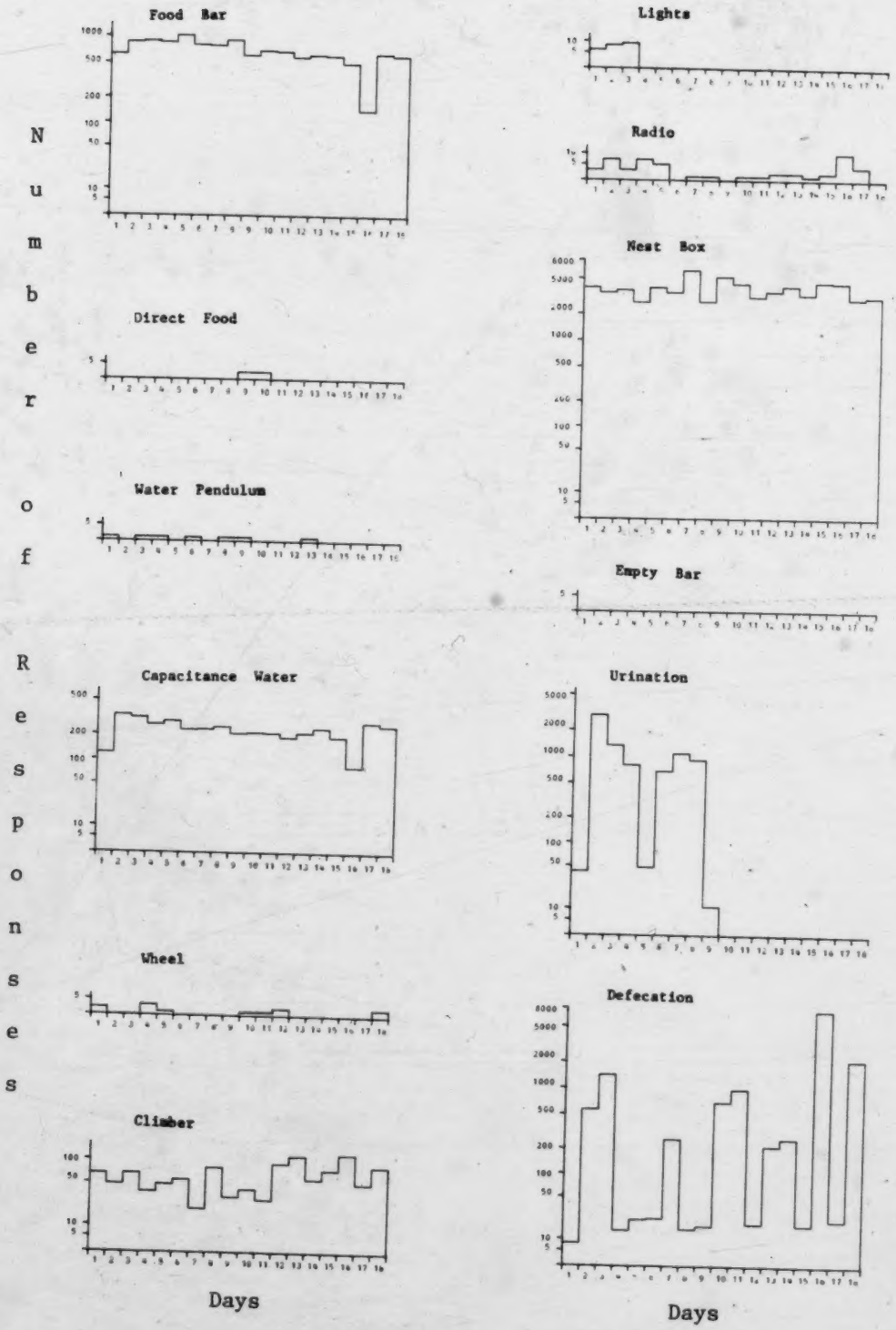

Figure 2. Daily total number of responses made by second animal on each variable.

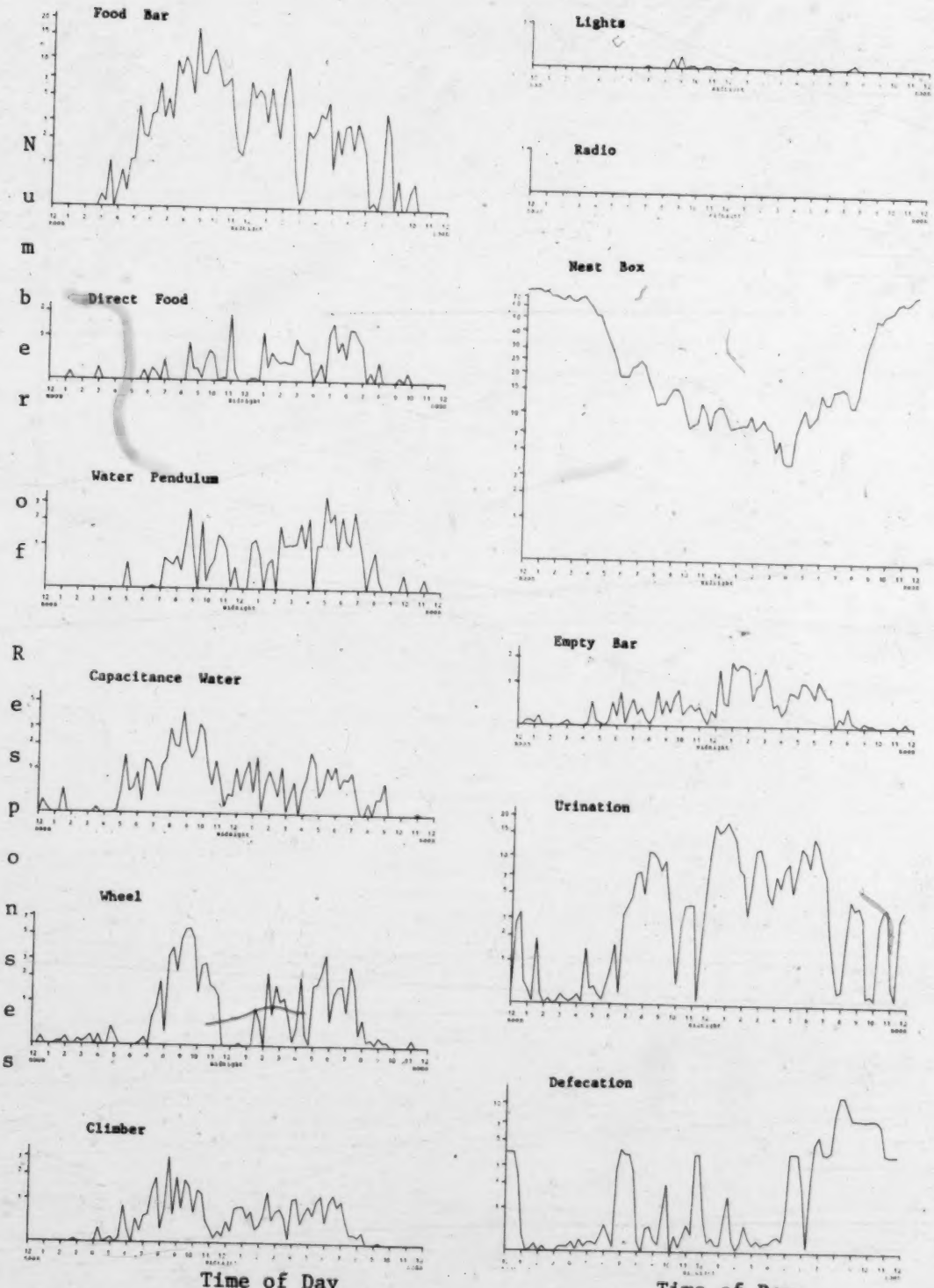

Figure 3. Average across days of number of responses made by first animal in each fifteen-minute interval throughout the day.

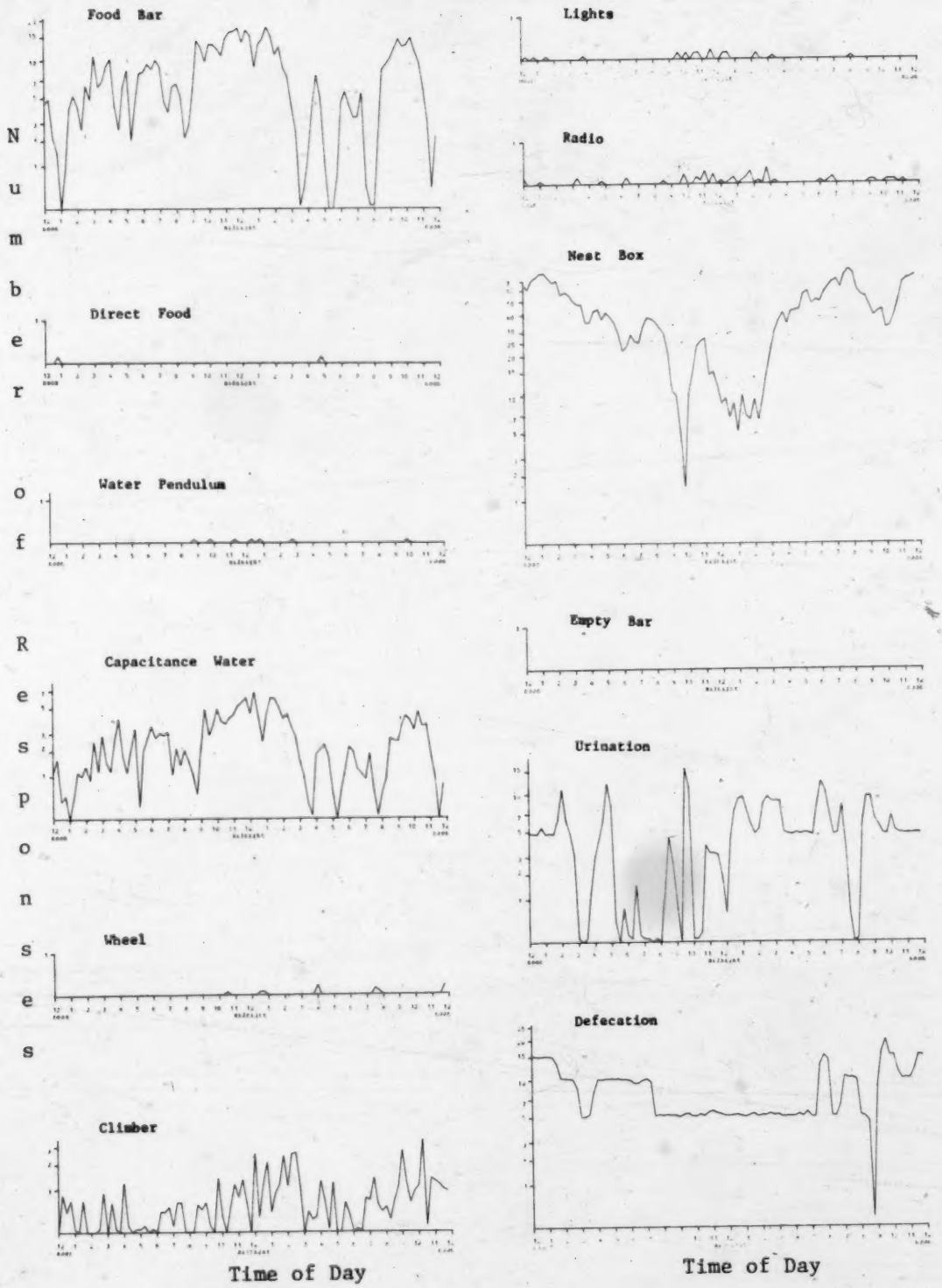

Figure 4. Average across days of number of responses made by second animal in each fifteen-minute interval throughout the day.

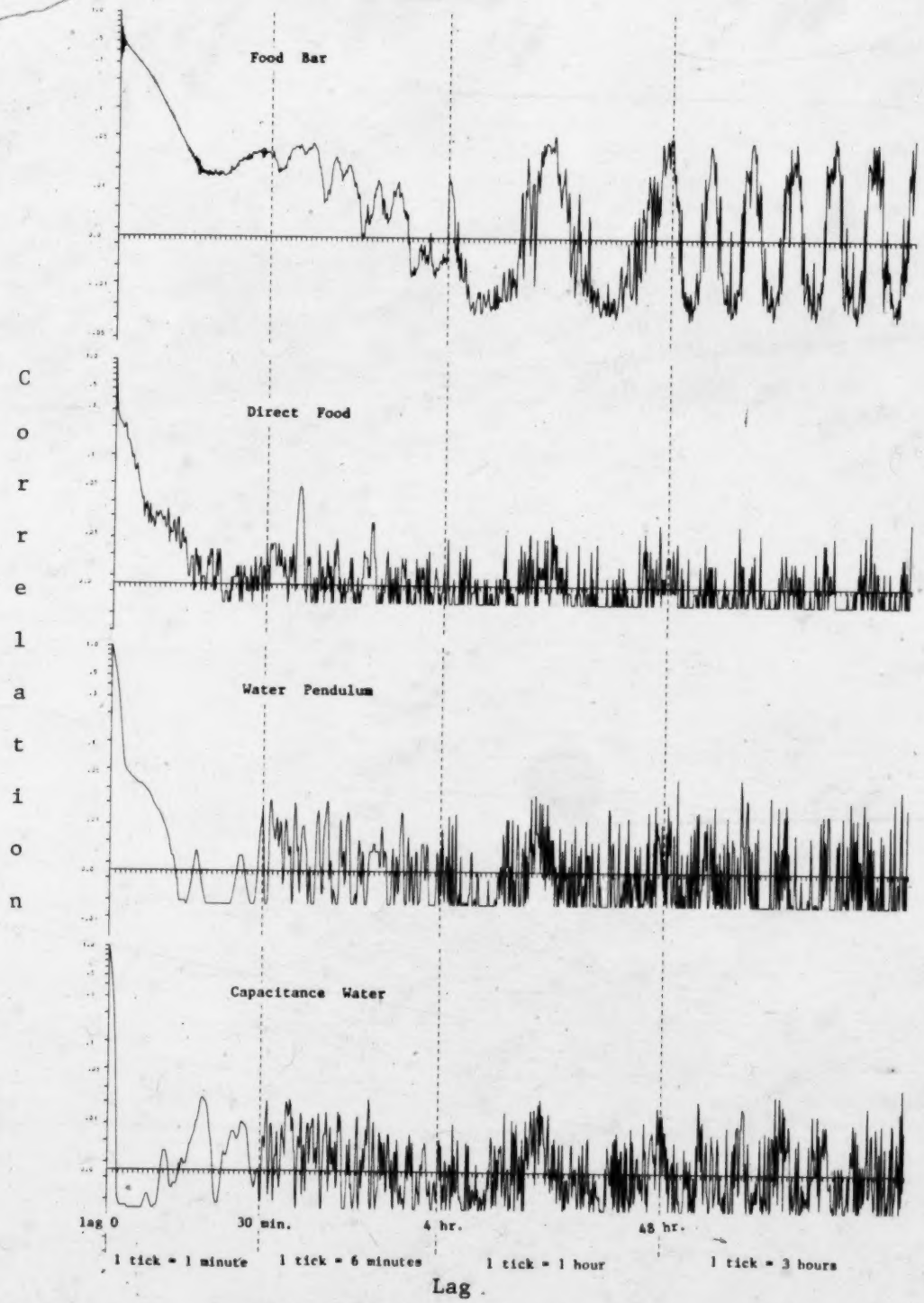

Figure 5. Autocorrelations of data for first animal.

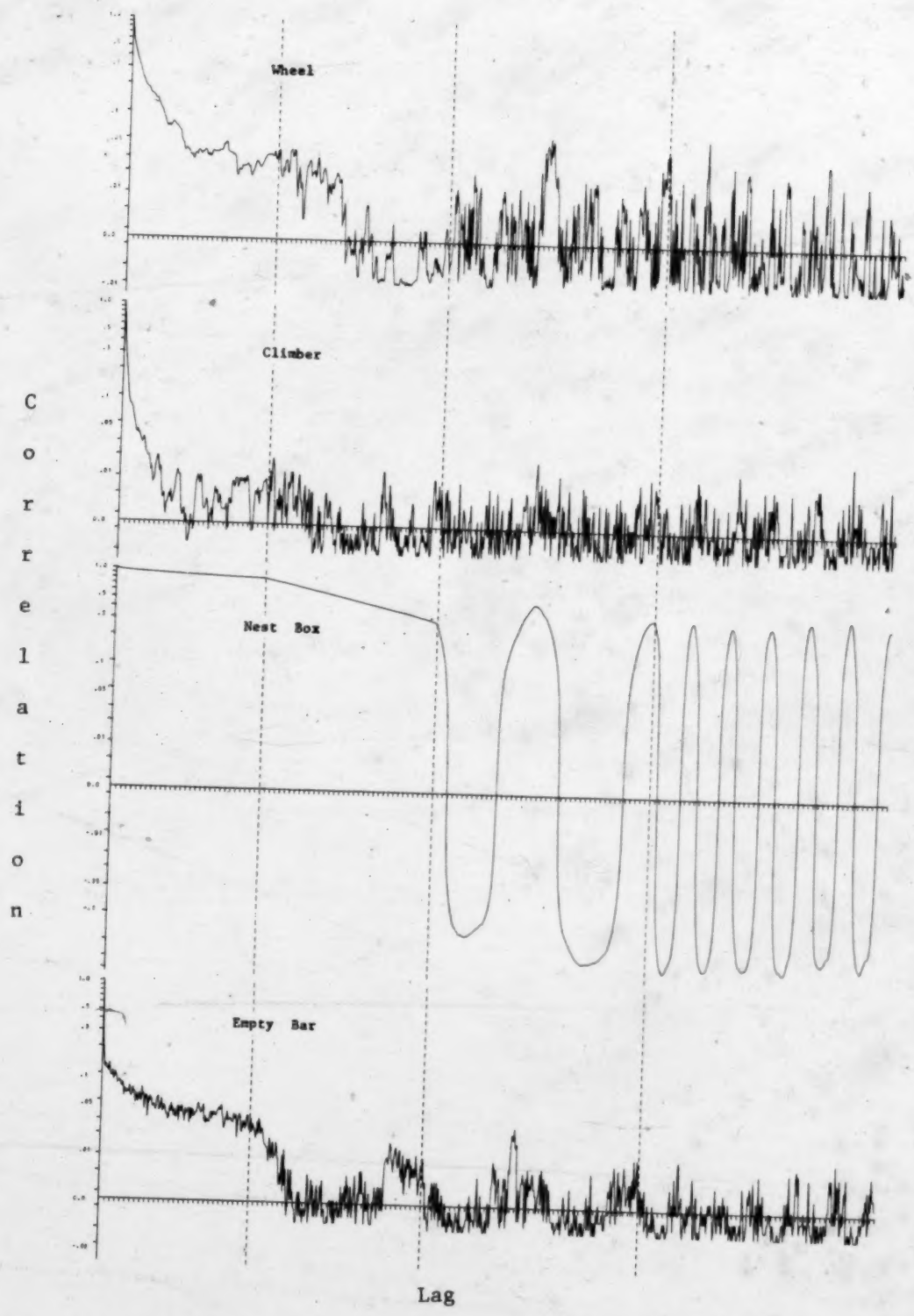

Figure 5. continued

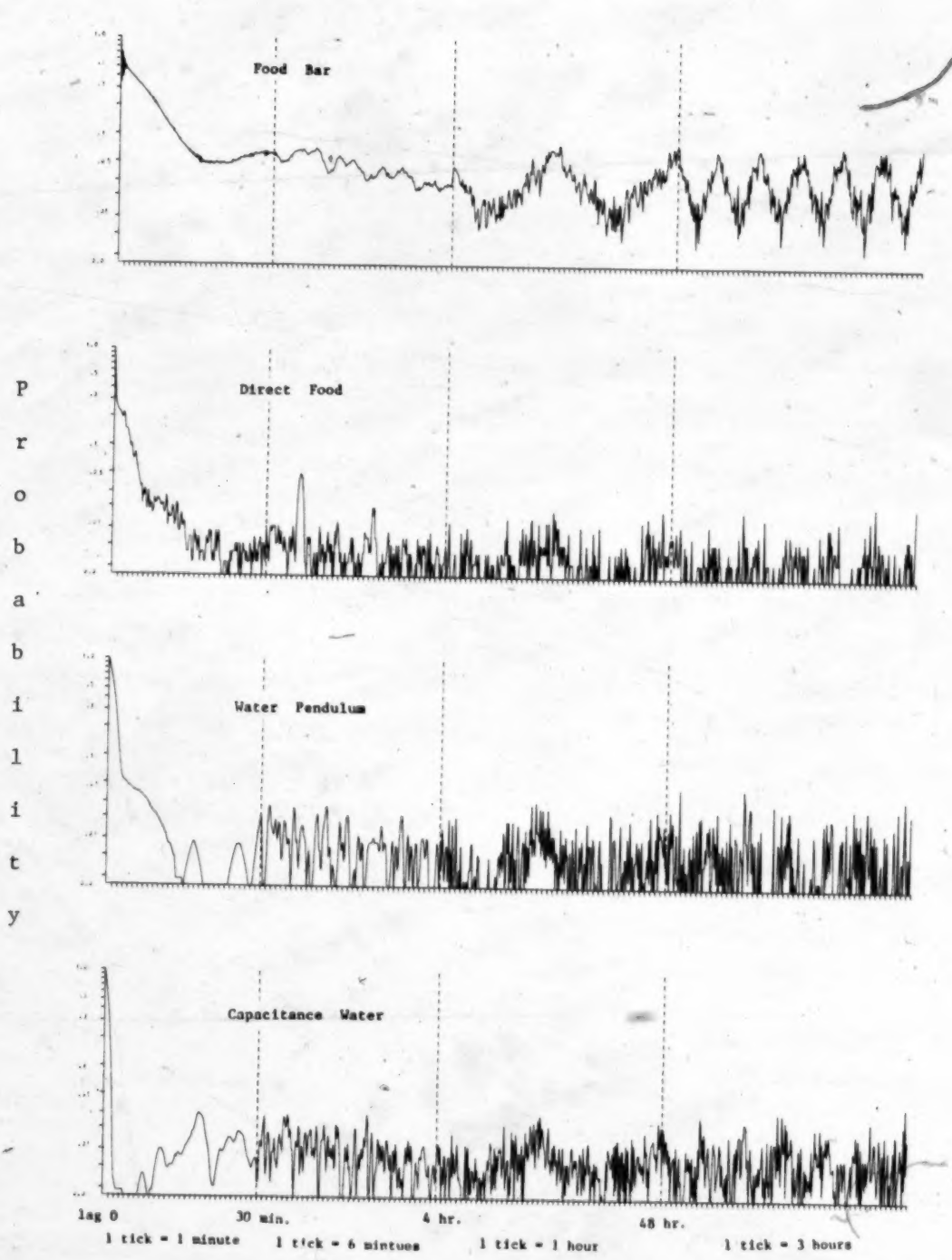

Figure 6. Lagged conditional probability of recurrence of same type of event for first animal.

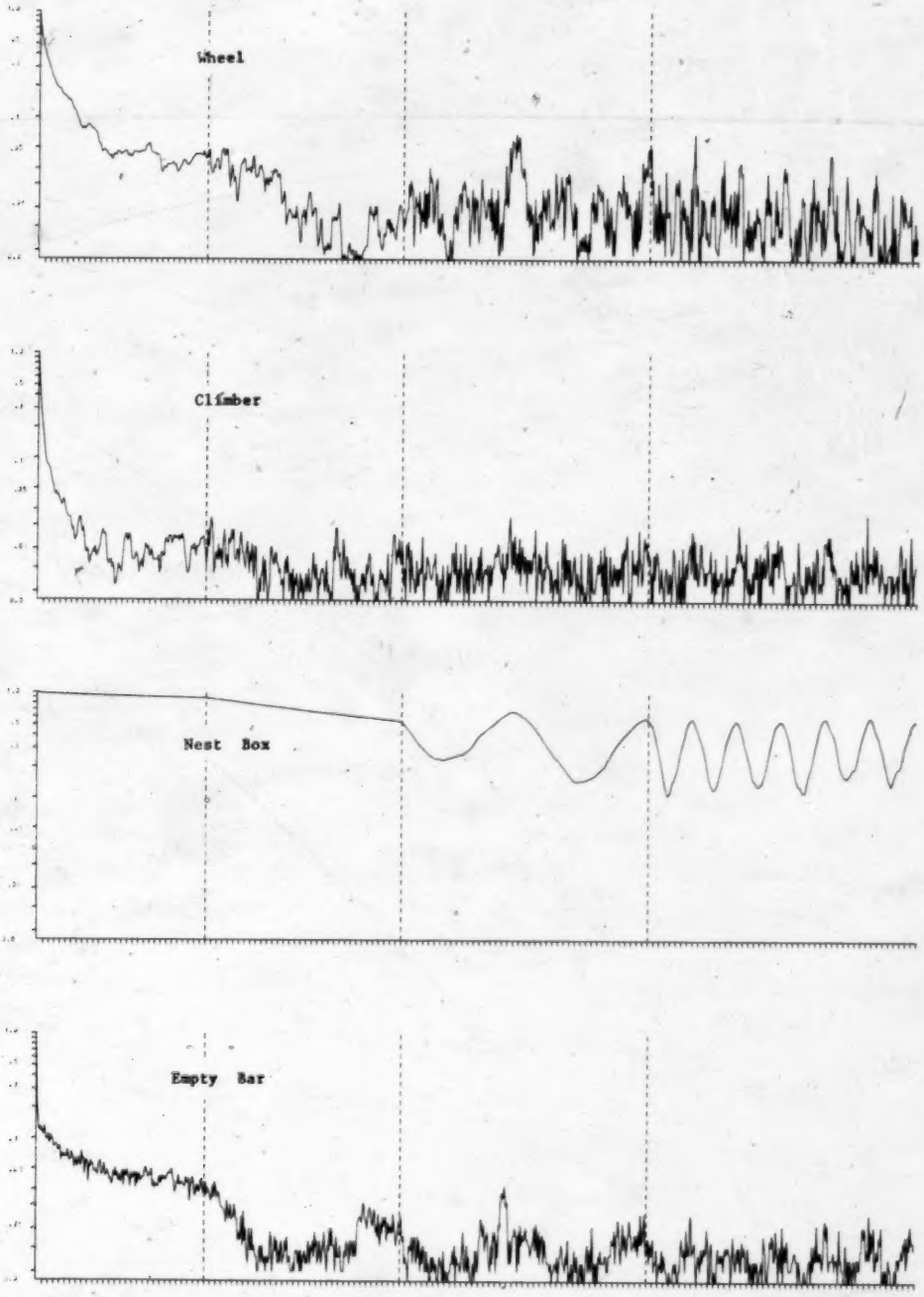

Figure 6. continued

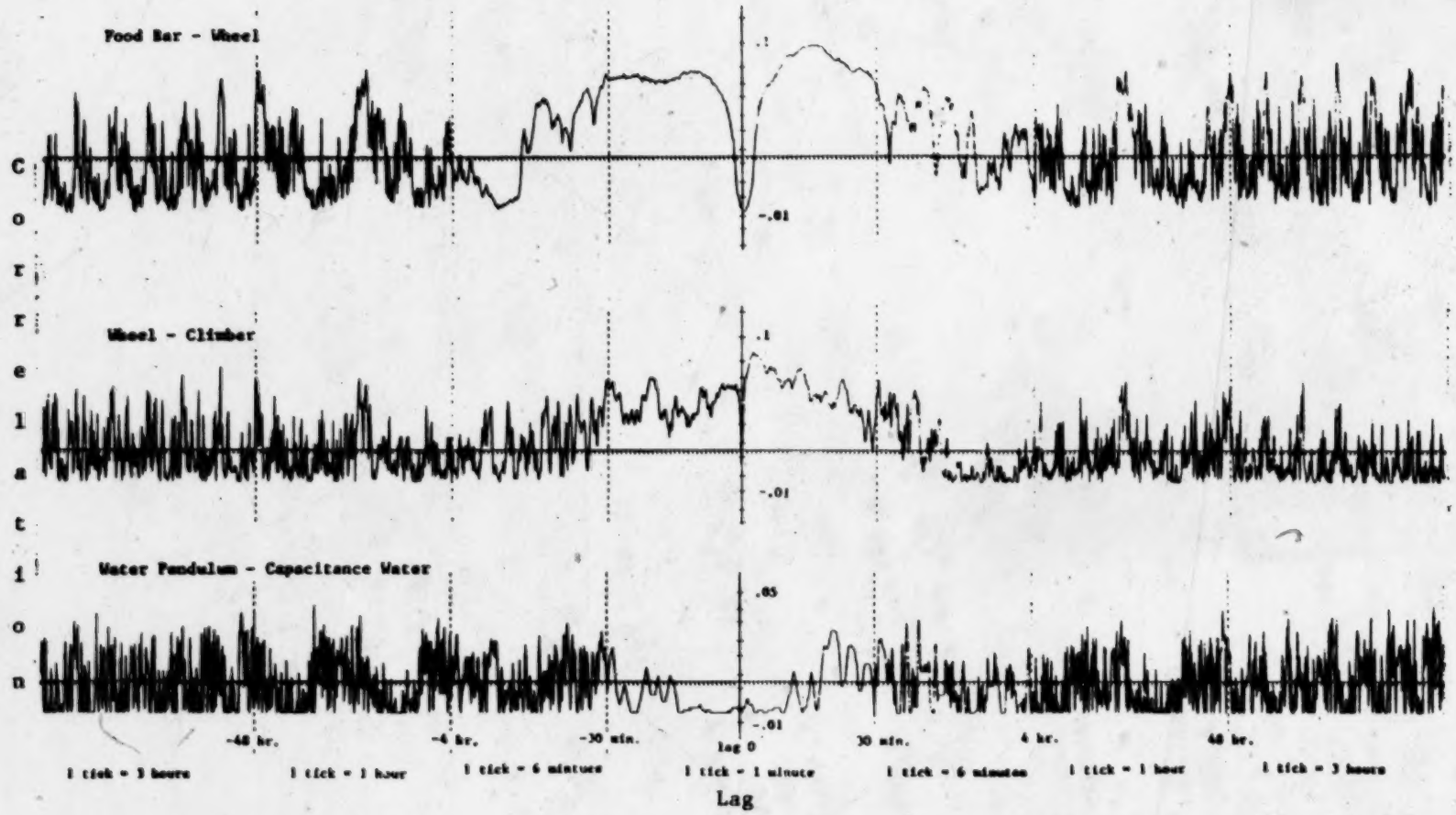

Figure 7. Selected graphs of lagged cross-correlation of first-named variable leading second-named variable for first animal.

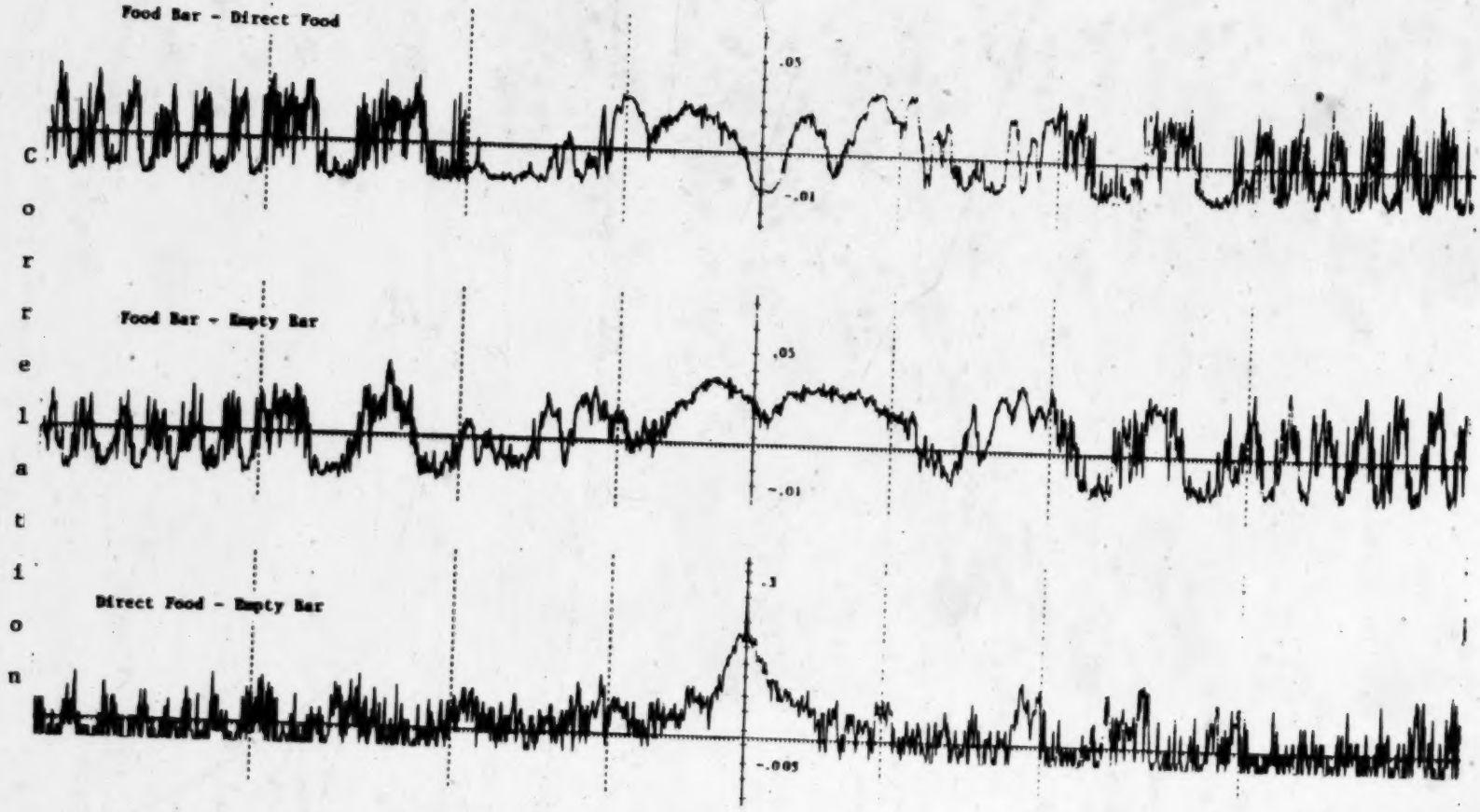

Figure 7. continued

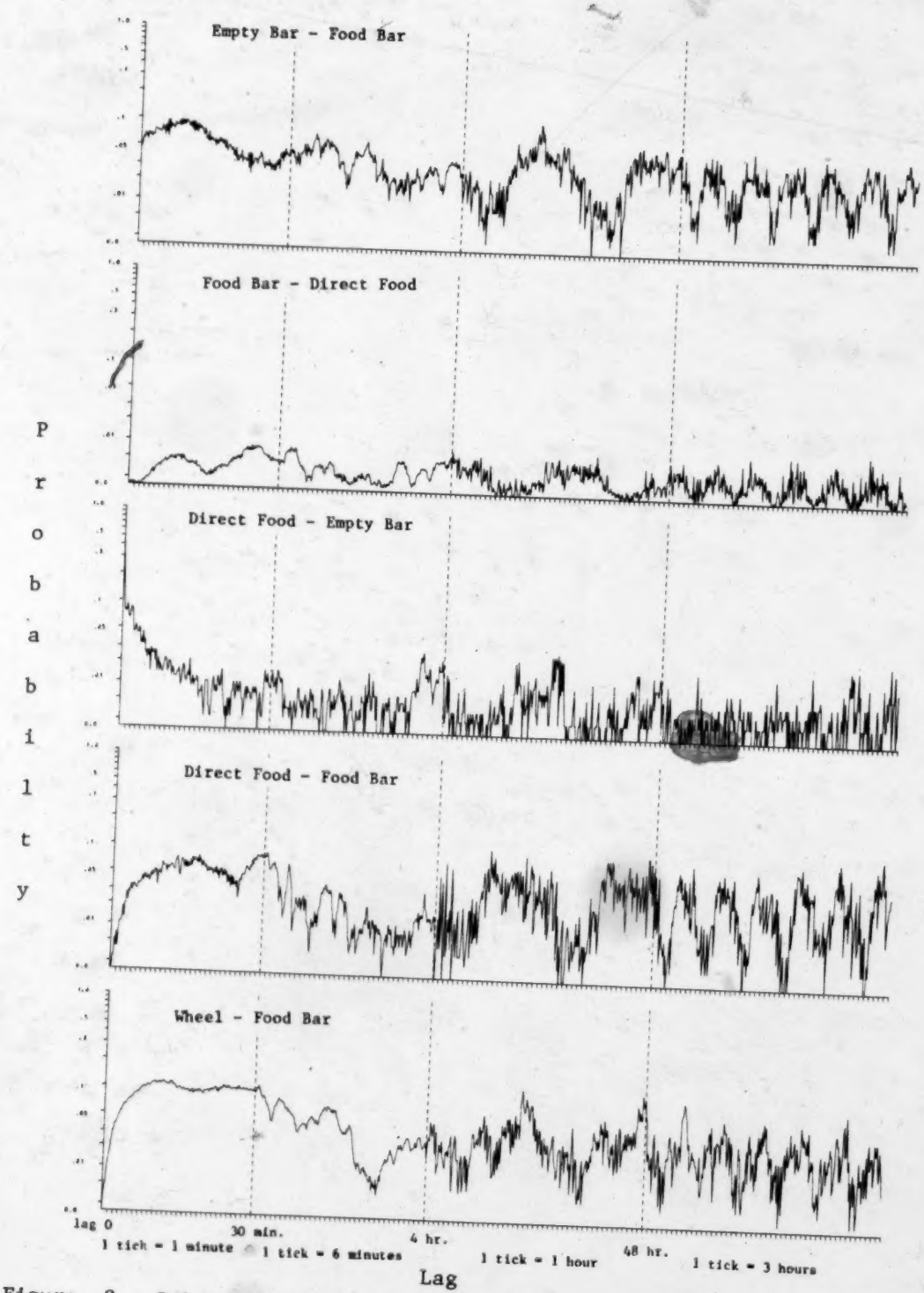

Figure 8. Selected graphs of lagged conditional probability of first-named event followed by second-named event for first animal.

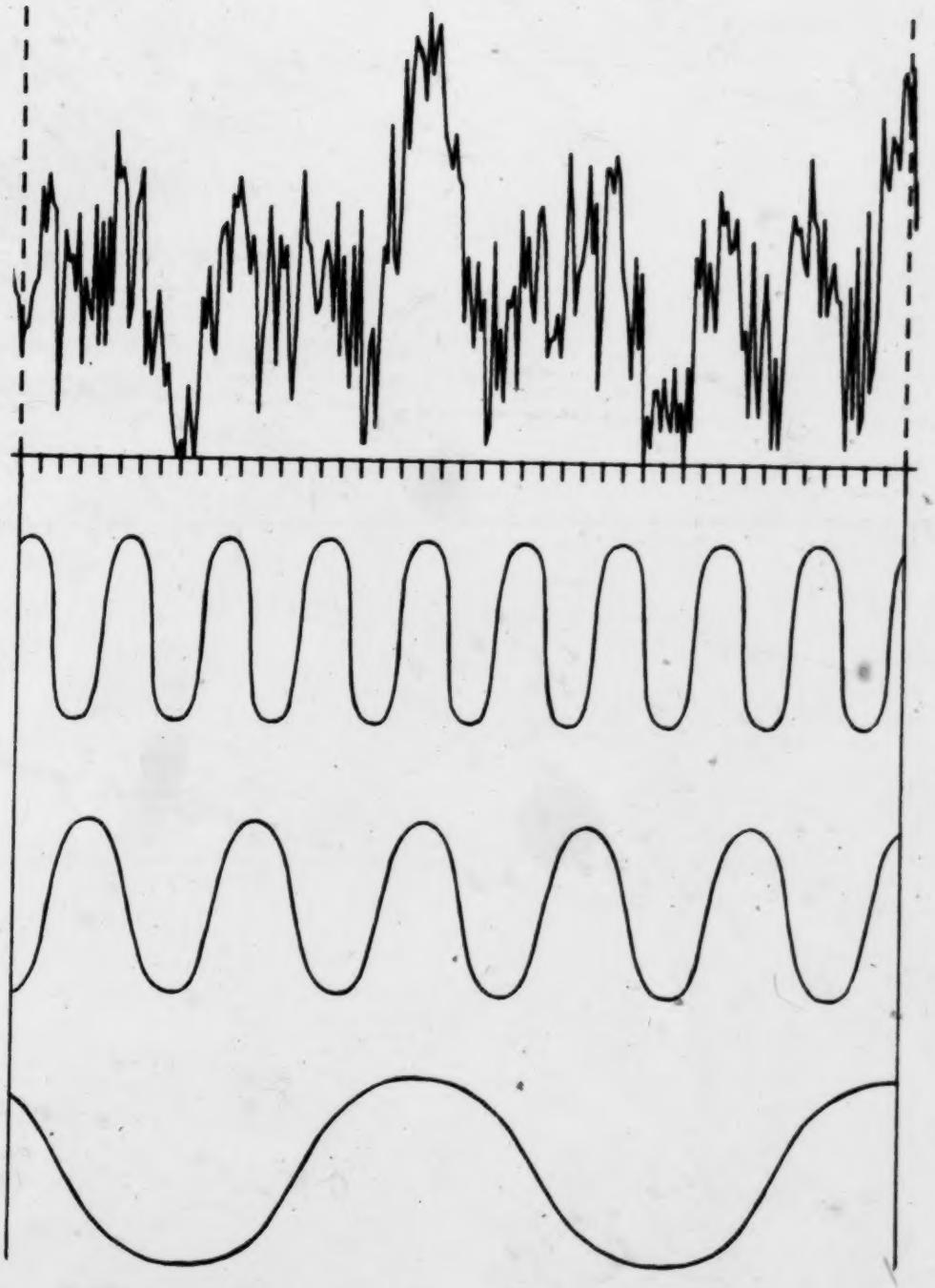

Figure 9. Conditional probability of Wheel following Wheel at lags of four hours to forty-eight hours with sketch of principal frequency components.

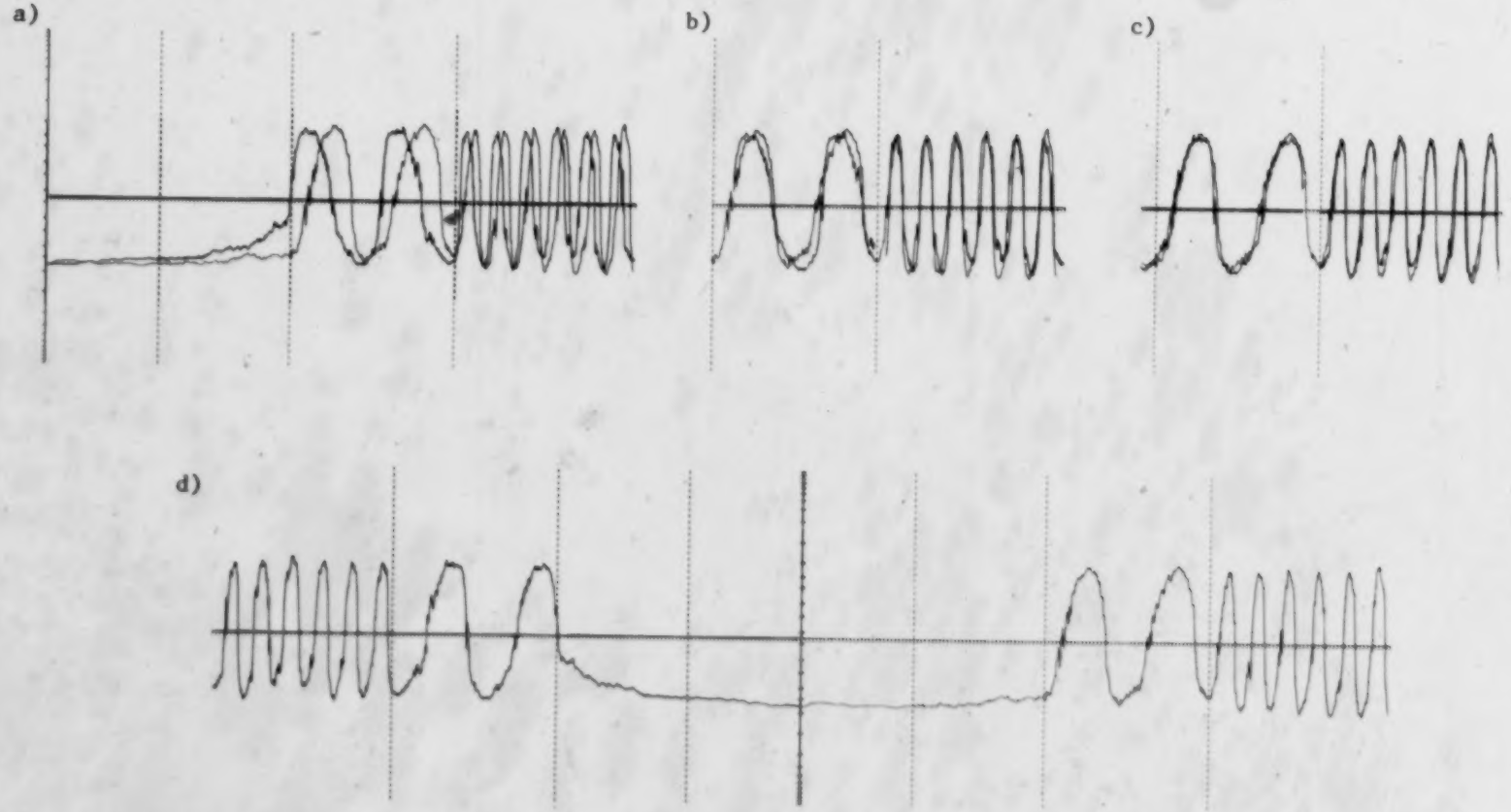

Figure 10. Periodic but asymmetric nature of the lagged correlation of Nest Box and Capacitance Water.
a) the two graphs of the correlations of these variables superimposed
b) sections from lag 4 hr. to lag 48 hr. and from lag 48 hr. to lag 8 days aligned to eliminate lateral displacement, exposing different shape of peaks
c) same sections with Nest Box leading sections reversed right to left, similarly aligned.
d) full periodic but asymmetric function obtained by reversing graph with Nest Box leading

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